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Proceedings
June 19, 1996

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Table of Contents

Department of Mechanical Engineering

"Dynamic Behavior of Composite Shafts with Automotive Applications"
Alan Argento

"Manufacturing Dependencies for Tasks, Fixtures and Dunnage Designs"
John Cherng

"An Elastoplastic Damage Coupling Analysis for Crashworthiness of Aluminum Tubes"
C. L. Chow

"Control of Dimensional Variability in Injection Molded Plastic Parts"
Pankaj K. Mallick

"Development of Fatigue Resistant Joints for Automotive Applications"
Pankaj K. Mallick

"Modeling and Optimization of Curing in Thick Section Laminated Composites Using Neural Networks"
Pankaj K. Mallick and Syed Murtuza

"Refrigerant Control of an Automobile Vapor-Compression Refrigeration System"
Eric Ratts and Andrew Bartlett

"Simulation of In-Cylinder Flows"
Subrata Sengupta

"Hydrocarbon and Oxides of Nitrogen in Lean Burn Natural Gas Engines"
Keshav Varde

"An Integrated System for the Design, Analysis and Manufacturing of Face-Hobbed Hypoid and Spiral Bevel Gears"
Yi Zhang

REPORT BRIEF

Function-Support Oriented Research on Distance Learning

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

AUTHOR	Roberto R. Kampfner Computer and Information Science
ASSISTANTS	Steve Rupp and Wendy Melton Research Assistants

BACKGROUND

Research on function support as a paradigm for the development of information systems has been carried out by the author of this project. The idea is to take the compatibility of the information system with the structure and dynamics of the organization using it as a basic design criterion. In the last few months, Steve Rupp and Wendy Melton carried out an independent research study project entitled "Interactive Distance Learning via the Internet and the World Wide Web." Such an effort has being continued to include access to personal computers to the developed environment for interactive conferencing supported with Virtual Places™ by Ubique, Inc.

OBJECTIVE

The idea of the project is to show what has already been obtained in terms of the development of a prototype environment for distance learning, and how this research can be extended to the support of other functions using the function-support underlying idea.

APPROACH

Our approach is twofold. It involves:

1) To show how the function-support oriented approach to systems development can be used in order to identify key requirements for the support organizational functions in a business, educational, or industrial environment.

2) To apply this approach to the develoment of support for the distance learning function, and to show how information technology can be used to meet these requirements.

- One basic idea is that information processing is an integral part of function.

Example 1: Information Processing in Natural Systems

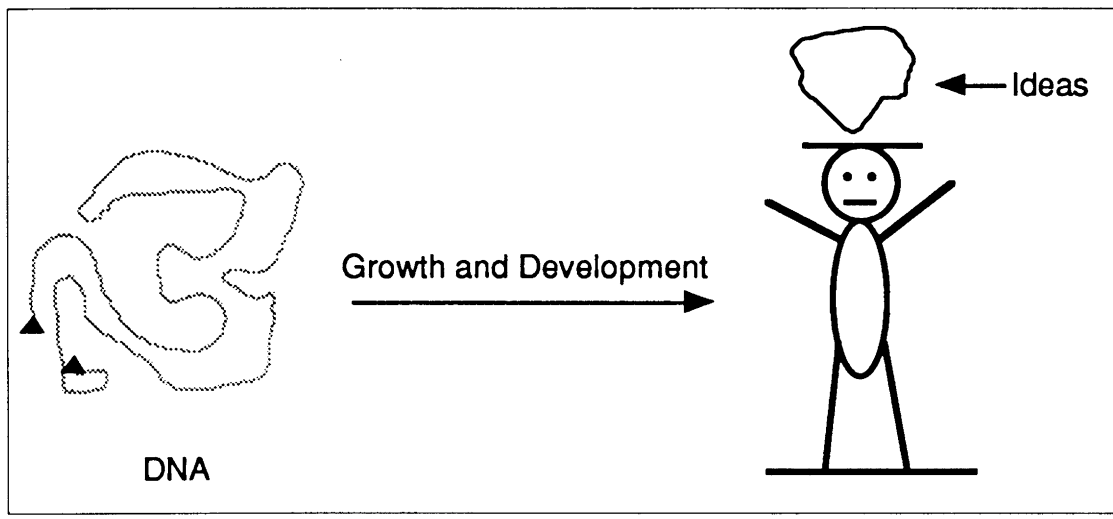
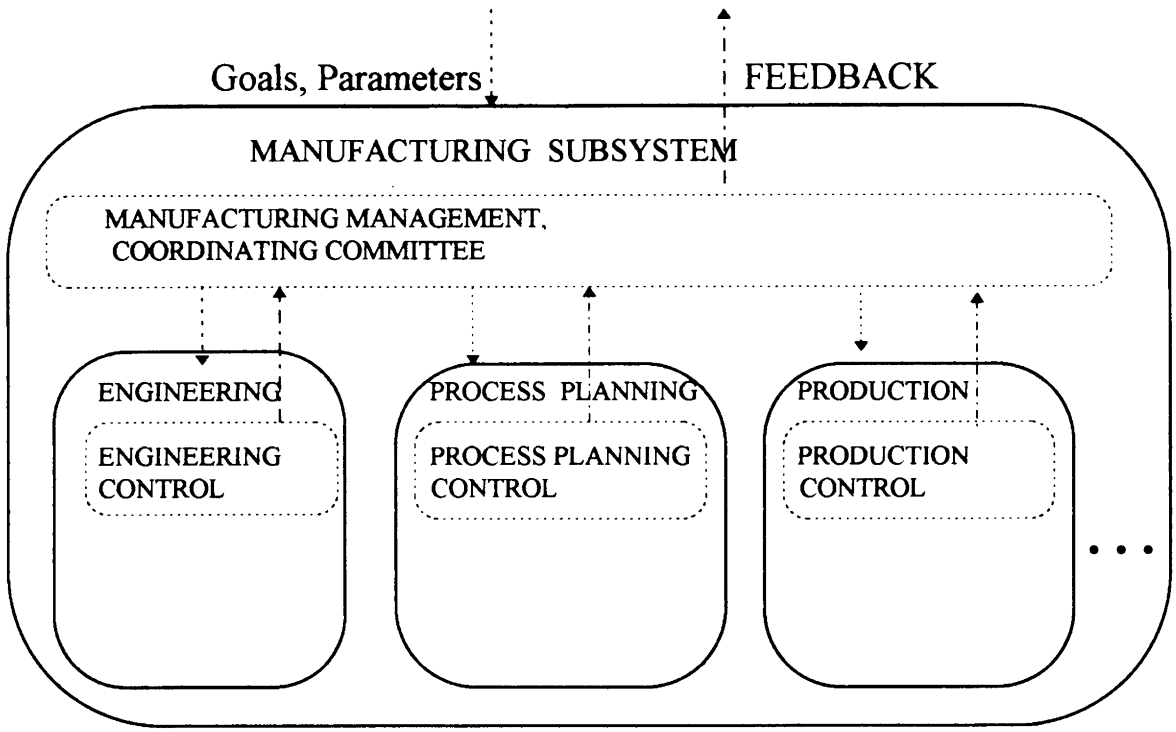


Figure 1. The information contained in the DNA guides the growth and development process.

- The importance of adaptability.
  Adaptability is essential in order to perform a function under environmental uncertainty.
- The importance of structure: hierarchical organization.
  Hierarchical organization implies some degree of specialization of function and the necessary coordination.
- Adaptive systems must have a hierarchical, distributed control in order to be able to cope with the uncertainty of the environment.
- Effective function support requires compatibility of information processing with the function.

Example 2: Information Processing in Organizations



The FEEDBACK is sent by each control subsystem to the control subsystem of its parent system, as indicated by the REPORTS-TO relation.

Figure 2. OCSM representation of an integrated manufacturing system.

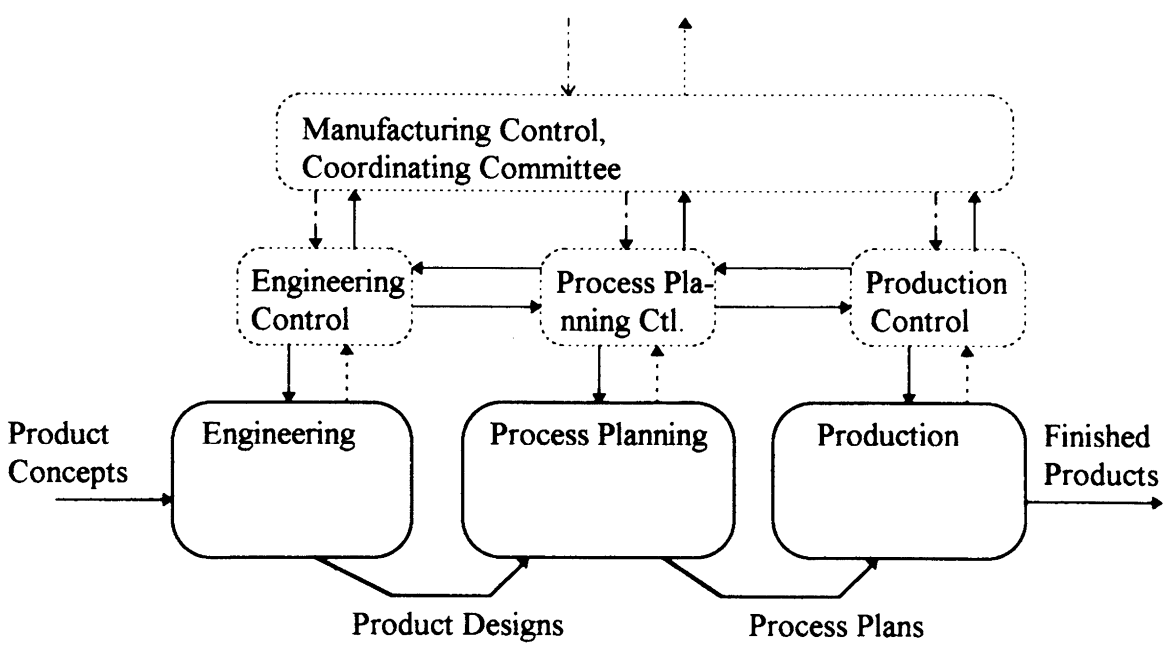


Figure 3. Informational interactions between the Engineering, Process Planning, and Production units

Example 3: Information Processing in Teaching/Learning

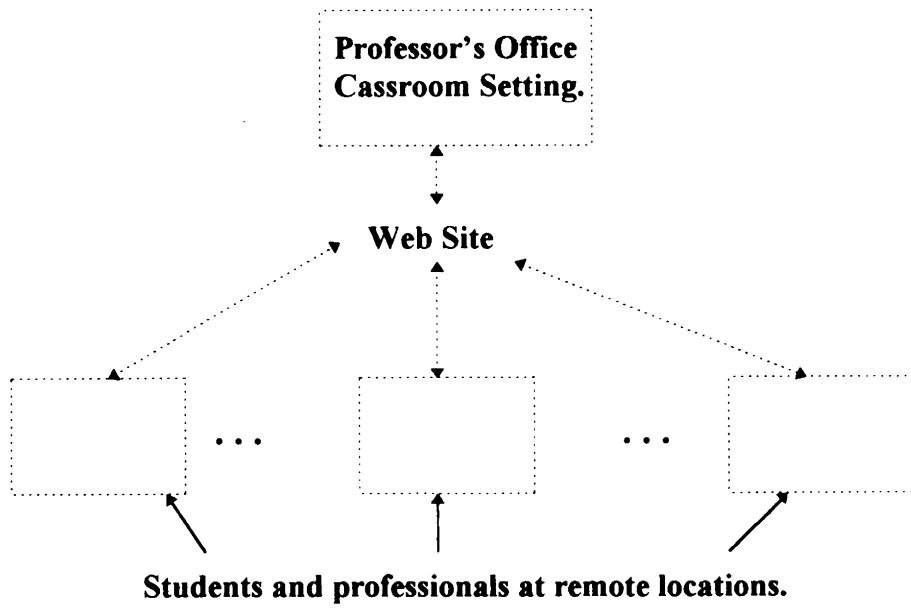


Figure 4. Support for Distance learning. With Software such as Virtual Places™ from Ubique, Inc., human presence and real-time interaction can be achieved in a classroom setting.

REPORT BRIEF

Information Technology, the Parable of the 67 Chevy, and an Ideal Vision

June 19, 1996

CATS COMPANY, TROY, MICHIGAN
TRO LEARNING COMPANY, MINNEAPOLIS, MINNESOTA
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

AUTHORS	Kenneth L. Modesitt and Bruce Maxim Department of Computer and Information Science	
PARTNERS	Greg Slack CATS Company	Dennis Ratica TRO Learning
ASSISTANTS	Rick Freiberg and Kumsuk Hartwig Research Assistants	

BACKGROUND

People do not like to waste valuable time. Over 80% of our undergraduate students work at least 20 hours/week and 98% of our graduate students work full-time. All of them commute, with every 10-minute daily round-trip commute to campus requiring *one work-week* on the road annually. Translate this to a fully-loaded engineer (100% overhead), and the cost easily exceeds $2,000 annually. Multiply by the appropriate factor in case you have *more* than a 5-minute drive from work or home to UM-D... This "simple fact" is a major reason for the role of information technology in the School of Engineering to enter a new phase. We are supplementing the use of computers and communication for relatively common-place applications, e.g., as a tool for problem solving by students. Yet the "parable of the '67 Chevy" (see Figure 1) shows that those who know the most about current situations are often the most reluctant to grasp the significance of new concepts. Moreover, this is a major paradigm shift from a mode emphasizing "teaching by professors" to one of "learning by students." See Figure 2 for why such a shift is desirable. An "ideal vision" for the community includes all of these individuals, organizations, and practices. This is part of a more holistic effort for building a "Distributed Intelligent Community" involving UM-Dearborn (see Figure 3).

OBJECTIVE

Supplement current practices related to information sharing with a more accessible delivery mechanism used by learners (students and faculty)

- at the university
- in the work place
- in community colleges
- while traveling on business
- at home

APPROACH

Provide asynchronous learning opportunities via:

- proven integrated and comprehensive educational software (courseware), using PLATO®

- interactive video conferencing using PictureTel®
- desktop video conferencing via Quick-Cam®
- Internet—for information content and collaborative processing

RESULTS

Several CIS courses have used the Internet and desktop video conferencing during 1995/96. Usage included the study and implementation of such systems, as well as the use thereof to provide learning asynchronously. During the spring term, remote dial-in from student homes to the CIS server permitted two students to view the same screen simultaneously, thus permitting collaboration on software development concerns. The integration of PictureTel and Quick-Cam video conferencing and PLATO is planned for the fall 1996, in at least two courses: Data Structures and Software Engineering. A pool of high-speed modems and Quick-Cams is planned for check-out by students and faculty for access to CIS campus computing resources from homes and business offices.

CONCLUSIONS

This pilot test is worth expanding to additional courses and markets, on an as-need basis. Some markets for the courseware/desk-top video conferencing will include those of continuing engineering education.

IMPACT

A high-quality educational learning experience will be more accessible to individuals and organizations on demand. Students will spend more time learning instead of commuting. Industry and their employees will save valuable time and money. The same will be true for students at the university and participating community colleges.

ACKNOWLEDGED Dean Sengupta of the School of Engineering, CATS (Greg Slack), TRO Learning Corporation, Comweb and Intel.

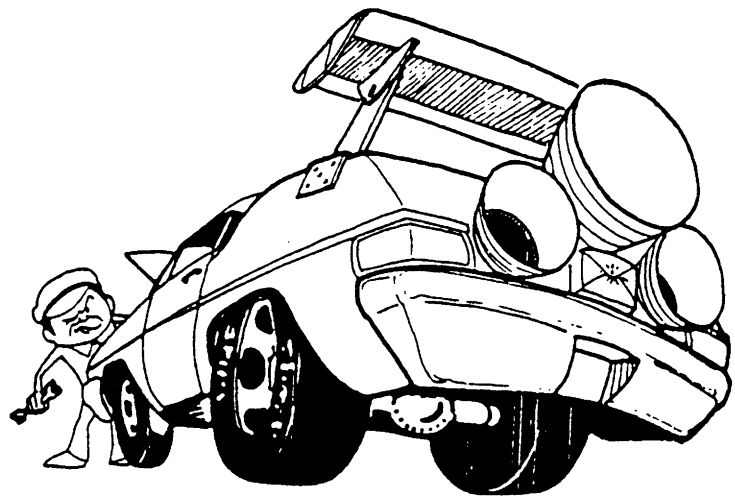


Figure 1. '67 Chevy

Once upon a time there was a man who wanted to be able to get from New York to Los Angeles on 12 hours' notice. His means of transportation was a 1967 Chevrolet that had bald tires and fired on three cylinders. Recognizing the deficiency of his means, he had the car tuned up and bought new tires, a supercharger, and a radar detector. Performance improved 87%, but he still couldn't get from New York to L.A. in 12 hours.

He next put in a Cadillac engine and added streamlining—still not fast enough. His last gasp was to install a turbine engine and aerodynamic controls, which got him to 200 m.p.h. on the interstates (within reach of what he needed) but led to bad scenes going through small towns.

When last heard of, he was complaining about problems with his turbine engine and small town police; he had not realized that he was trying to improve the performance of a basically wrong means of transportation. He was also asking about contrails and, when told about jet airplanes, said, "They'll never fly."

Morals

- If you're using the wrong tool, improving its performance won't help much.
- The people who know the most about existing tools are often the hardest to get to accept better and different ones.
- The development of new tools seldom makes the existing ones totally obsolete. Even if our man had accepted jet airplanes, he would still have needed his '67 Chevy for getting to the grocery store.

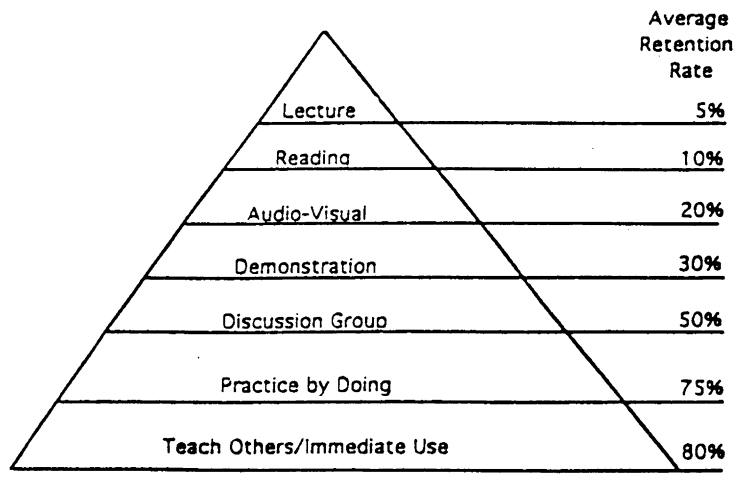


Figure 2. The Learning Pyramid [National Training Labs, 1994]

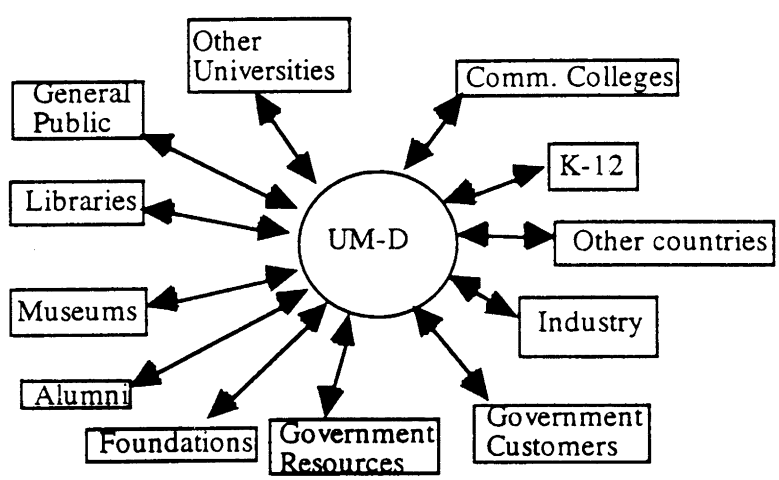


Figure 3. The Distributed Intelligent Community of UM-Dearborn [Modesitt, 1995]

REPORT BRIEF

OBJ-NET: An Object-Oriented System Design Tool

June 19, 1996

RESEARCH EXCELLENCE AND ECONOMIC DEVELOPMENT FUND
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

AUTHORS	David H. H. Yoon and Qiang Zhu Computer and Information Science
PARTNER	Jie Cheng Ford Motor Company
ASSISTANT	Vidya Mohanram Research Assistant

BACKGROUND This project has been funded by Ford Motor Company and the University of Michigan-Dearborn through REEDF.

OBJECTIVE To develop a system design tool which will help system designers:

- To interactively specify complex systems in terms of icons and connectors
- To test and modify the system designs
- To integrate the existing systems
- To simulate and refine the existing systems

APPROACH The existing system design approaches are:

- Process-based methodologies
  JSD, SADT, MASCOT
- Object-based methodologies
  HOOD, MOON, ADM3
- Net-based methodologies
  Hierarchical Colored Petri Nets

OBJ-NET is based on objects and nets. An object is defined as a computational model or an abstraction of a real-world entity. Real-world entities such as AGVs, robots, machines, conveyors and workers can be viewed as objects. An object consists of hardware, software, and interface. An object accepts input and produces output. A net represents the flow of control between and across various objects. In OBJ-NET, objects will be represented as icons and nets will be represented as connectors. In OBJ-NET, a system is viewed as a hierarchy of objects and sub-objects as shown (Figure 1).

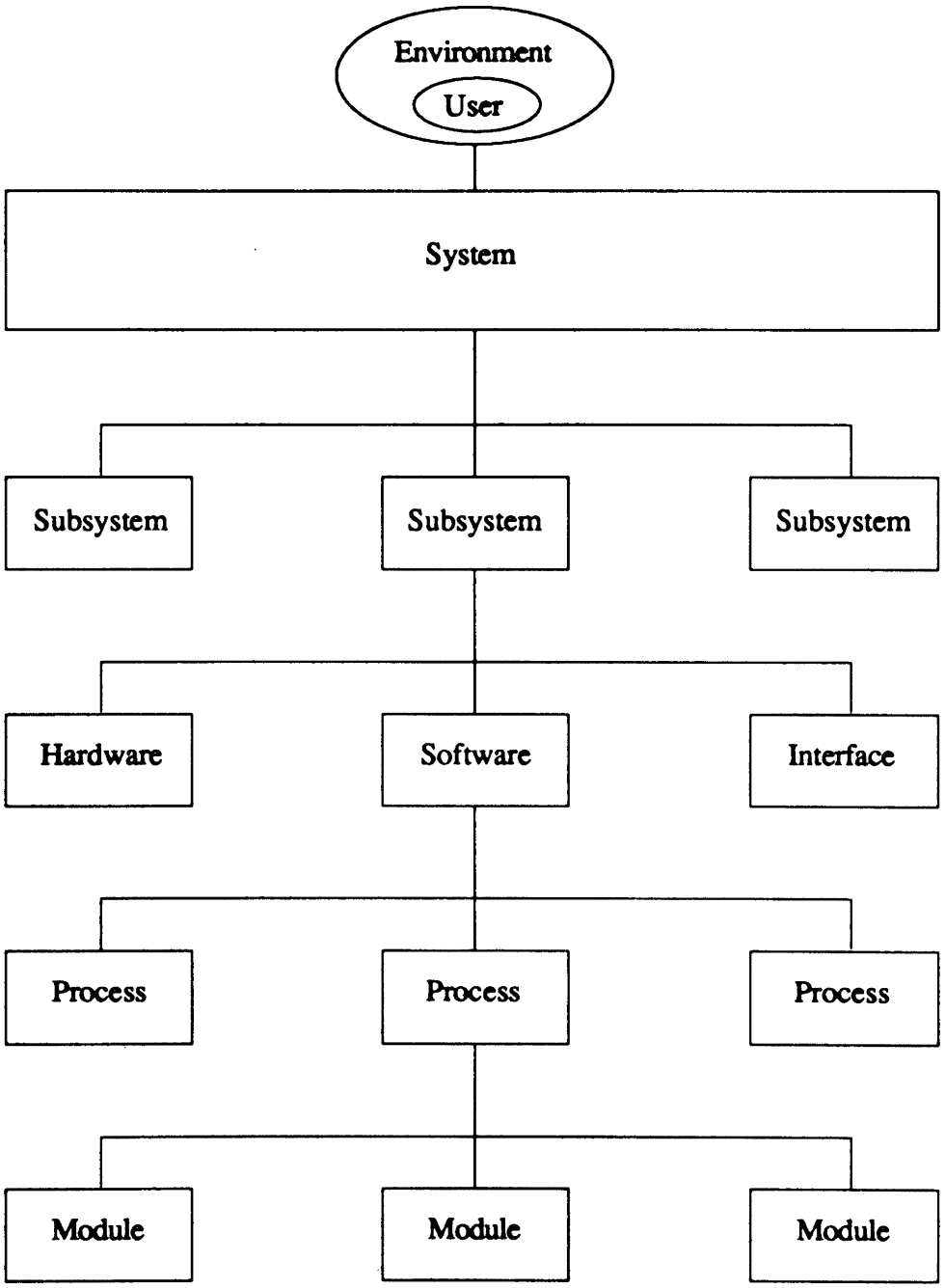


Fig 1: OBJ-NET system hierarchy

IMPLEMENTATION Due to the decomposablity and connectability of objects, the X window system has been chosen as the basis of the OBJ-NET system. The OBJ-NET environment can be viewed as in Figure 2. The various applications interface with X window system using X lib and OBJ-NET. It is being implemented using Tcl/Tk and C under X windows.

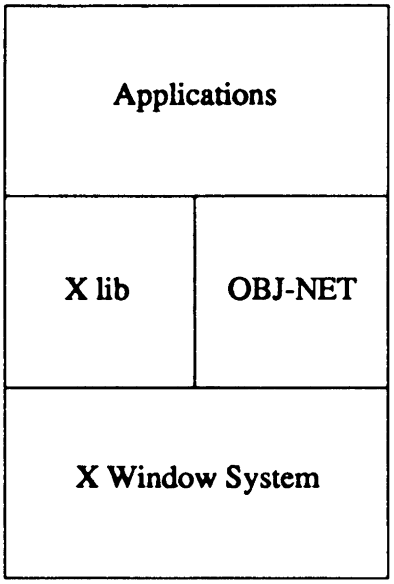


Fig 2: OBJ-NET environment

RESULTS

OBJ-NET is the first of the category and is based on the Object-Oriented system theory which professor Yoon has been developing for the past few years. The major components of OBJ-NET system are:

- System Menu
- Icon Editor
- Application Developer
- Simulator

Currently, OBJ-NET supports system, subsystem, process, and module icons and one-way and two-way connectors. This will be extended to encompass more icons and connectors. Currently the icon editor (Figure 3) is being developed. The application developer and simulator will be developed during the next phase of the project.

IMPACT

The principles behind OBJ-NET can easily be extended to the design of hardware and the codesign of hardware and software. OBJ-NET would enable modeling of complex, real-time, distributed systems. OBJ-NET simulator would enable testing and streamlining of interfaces between multiple systems.

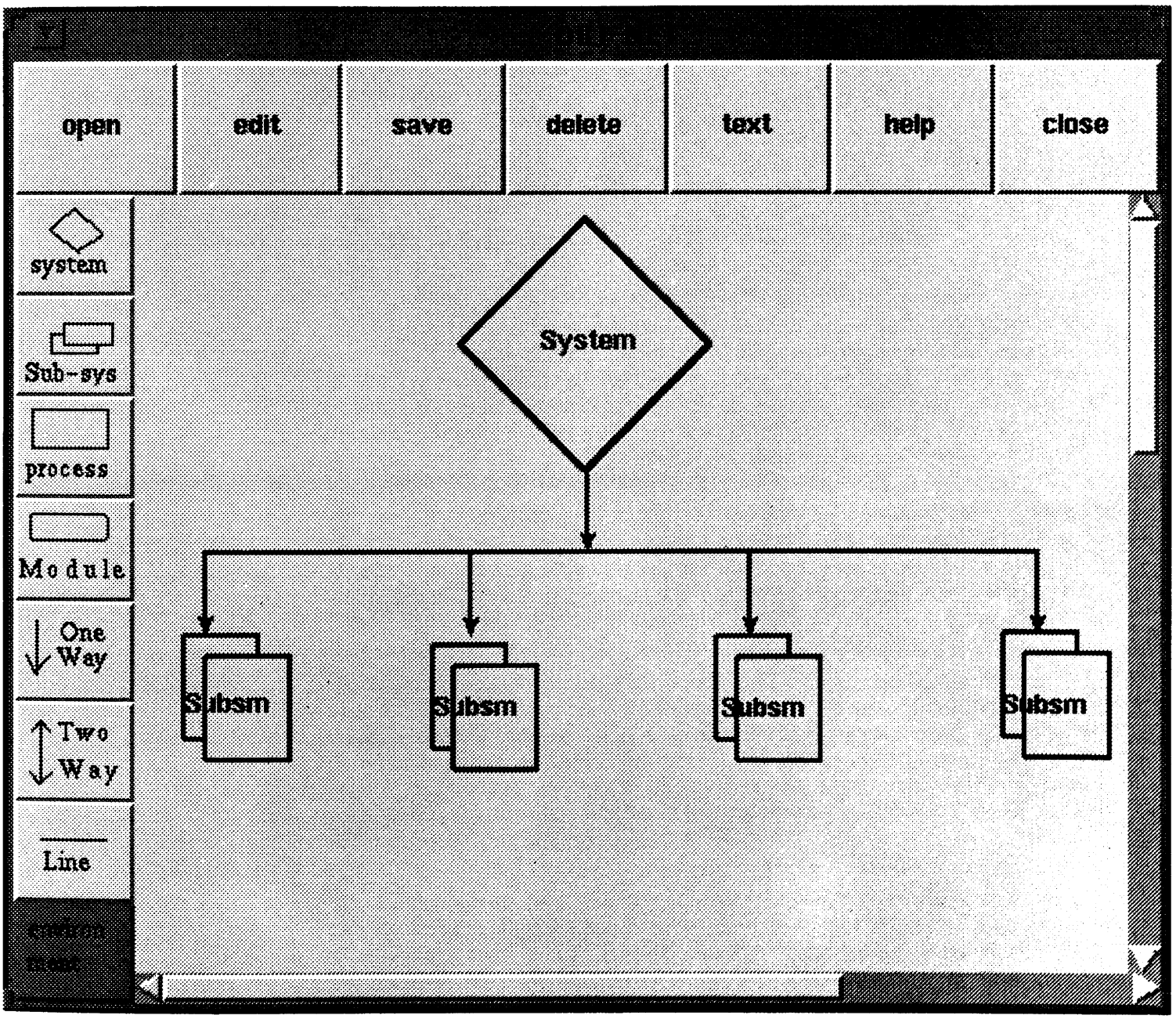


Fig. 3: OBJ-NET Editor

REPORT BRIEF

Computer Aided Speech Fluency Treatment

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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ASSISTANT	Louis Prezbienda (Acromag) Research Assistant

BACKGROUND

Stuttering is a serious communication disorder that afflicts more than 2-1/2 million individuals in the United States. However, stuttering can be remedied to functional speech fluency with appropriate speech pathology treatment. There are many clinical approaches to treating individuals who stutter. However, the treatment process can take months of repeated procedures that are costly and overly generalized. Therefore, there is a need to develop a cost-effective, computer-based system that could assist stuttering individuals in improving their fluency skills in their own homes on a daily basis.

OBJECTIVE

The objective of this proposal is to develop a real-time fluency therapy aid that will be affordable to speech pathology clinicians and individuals who stutter. The computer-based system that will be developed will be a tool that can be used in the homes of the clients. This will improve their speech fluency control.

APPROACH

The speech fluency computer-based system is built around a personal computer (PC). In order to offer real-time operation, an additional add-in card with digital signal processing capability will be developed. The software written will be user-friendly in order to aid the clients in improving their speech fluency tests. In addition, the software will record the progress of the clients such that the results can be available during the doctor visits. The performance of the system will be fine-tuned through the comments and feedback obtained from the clients.

RESULTS

The software for the speech fluency treatment aid has recently been completed. It is currently being clinically tested at Beaumont Hospital in order to evaluate its performance. The software is currently running in real-time. However, it needs to be fine-tuned to avoid unexpected crashes. Preliminary results are very encouraging.

Figure 1 shows the basic setup of the system. The patient's voice is captured by the microphone, then is processed by the sound blaster and computer. The energy signal is then plotted versus time as shown in Figure 2. Notice that there is a time bar that scrolls across the screen which is an indicator of where the client should be with respect to the goal energy profile. A typical screen is shown in Figure 3, where the client's signal and the goal signal are displayed. The patient is always trying to match the goal signal. Notice the

buttons on the top of the screen. They enable the user to playback his/her sounds. This is helpful to the patient because it gives him/her an immediate feedback. Also, the setup has a system to assess the performance of the patient. The parameters measured include: start alignment, end alignment, slope onset, magnitude, and general shape. A score of great, good, or bad is given for each measured parameter of the each utterance. The results are stored on disk to enable the doctor to review the patient's progress. Figure 4 shows results of a certain utterance.

CONCLUSIONS

Use of the average magnitude profile for the analysis and comparison of spoken utterances has been used extensively in the administration of stuttering therapy. The software being developed provides a means to transfer the administration of stuttering therapy into the homes of stuttering clients. A beta version of this software is currently under evaluation at William Beaumont Hospital and in the homes of clients of the hospital's speech and language department.

IMPACT

The project will impact undergraduate and graduate education through student involvement. Currently, there is one undergraduate and one graduate student involved in the project. Also, some courses will be enhanced by the project. These courses include: ECE 584 (Speech Processing), ECE 580 (Digital Signal Processing), ECE 480 (Introduction to Digital Signal Processing), ECE 431, and ECE 432. The course enhancement will be in the form of introducing new concepts regarding the use of speech processing to aid speech pathology. Also, the project could generate a software that can be commercially marketed to thousands of stuttering patients.

Software Only Version Hardware Diagram

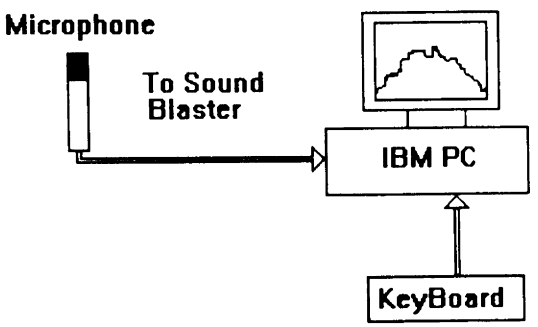

Figure 1.

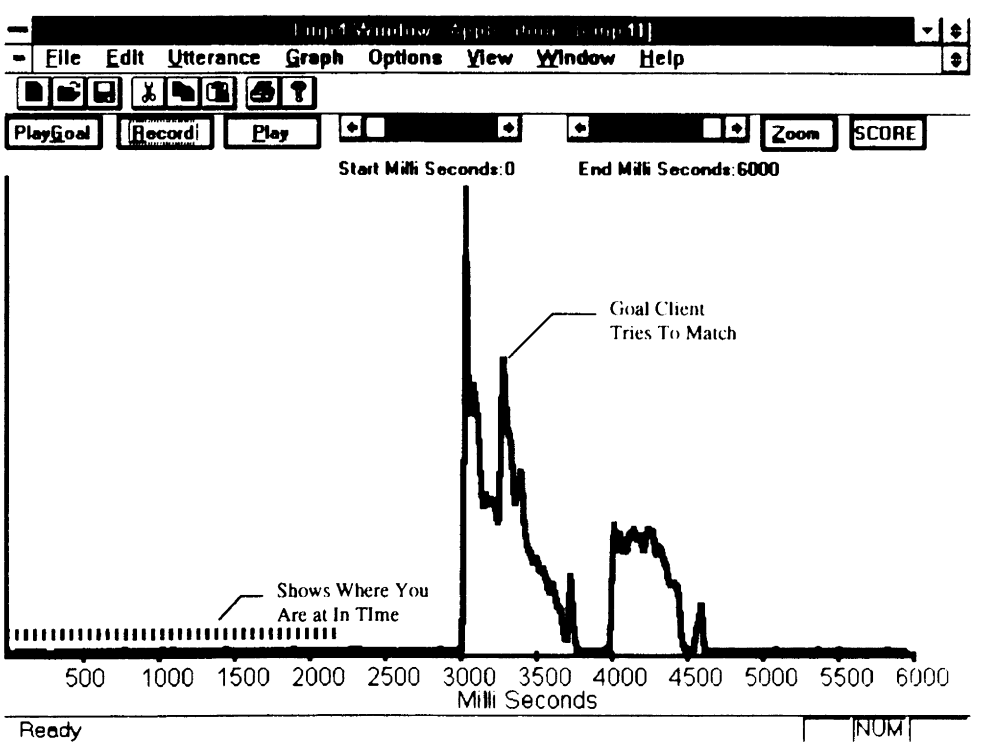

Figure 2.

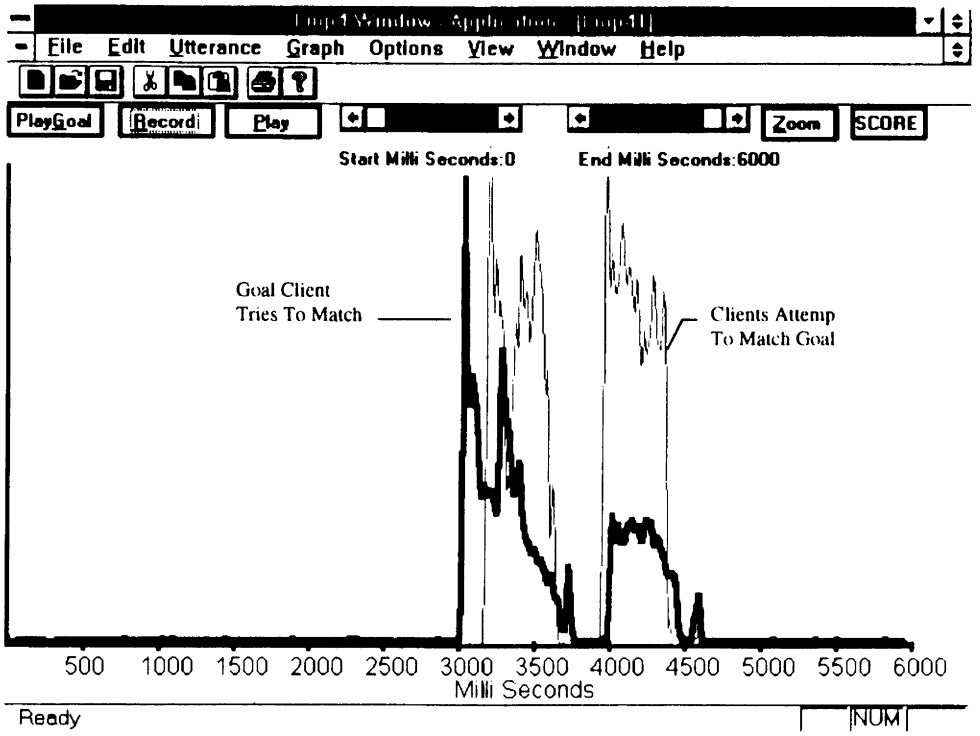

Figure 3.

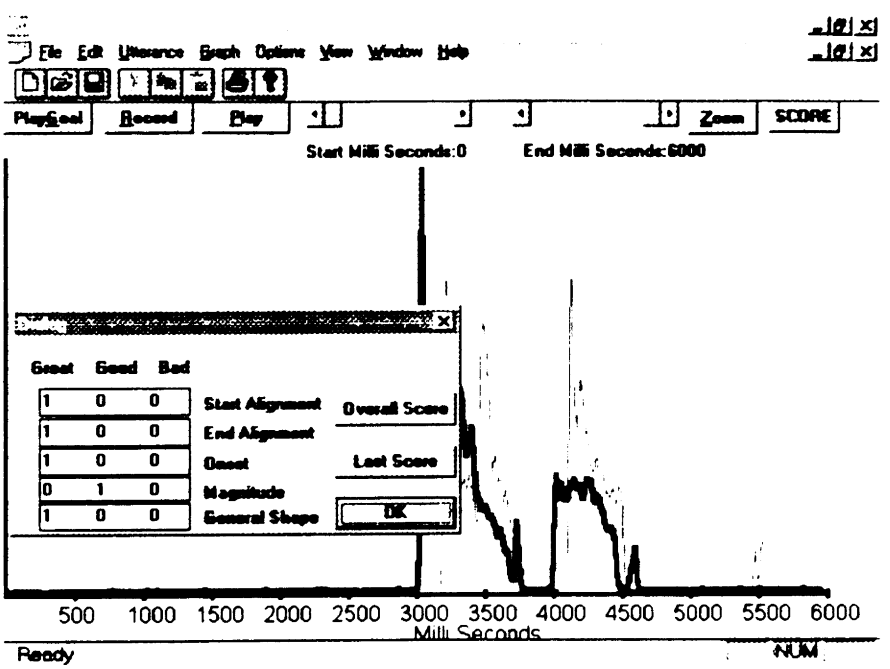

Figure 4.

REPORT BRIEF

LOIS: A Real-Time Lane Detection Algorithm

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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BACKGROUND

The ability to detect lane boundaries in color images of a road scene that is acquired from a car mounted visual sensor is an enabling or enhancing technology with significant impact on the next generation of automotive systems such as intelligent cruise control, lane departure warning, virtual camber, autonomous driving, and navigation.

OBJECTIVE

Robustly detect lane boundaries without prior knowledge of the lane structure or road location in the image. Do so under a variety of road pavement types and lane structures, and under various weather conditions.

APPROACH

To achieve this goal we have developed a new and novel solution to the lane detection problem. This solution inherits the best elements of both the edge-map-based approaches and the variational-template-based approaches that exist in current literature. This solution yields an algorithm which we have named the likelihood of image shape (LOIS) lane detection algorithm. LOIS finds lane locations efficiently and does so under a wide variety of lane, road, and lighting conditions. Furthermore, LOIS is a real-time algorithm that runs at up to 15Hz on a general-purpose Sparc10 workstation.

More specifically, our approach to the lane detection problem is explained as follows:

- We derive a parametric equation that each of the lane boundaries in a typical road scene image has to satisfy. Using this equation, we form a template image of lane boundaries. As template parameters change, the shape of the template lane boundaries deform. The template image and its deformations constitute a deformable template model of global lane shape (much like the work of U. Grenander, M. I. Miller, and others). Our objective is to deform the template (by changing the lane shape parameters) so that the corresponding lane boundaries "match" the ones in the observed image.
- In order to determine the deformation that best "matches" the observed image, we derive a function that does a relative ranking among the different deformations. This function

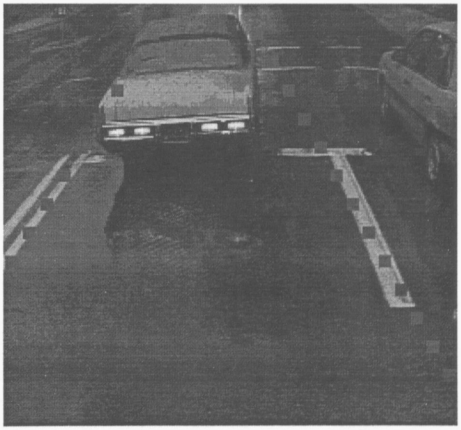
evaluates the degree to which the edge magnitude and direction in the observed image agrees with the one dictated by the deformed template.

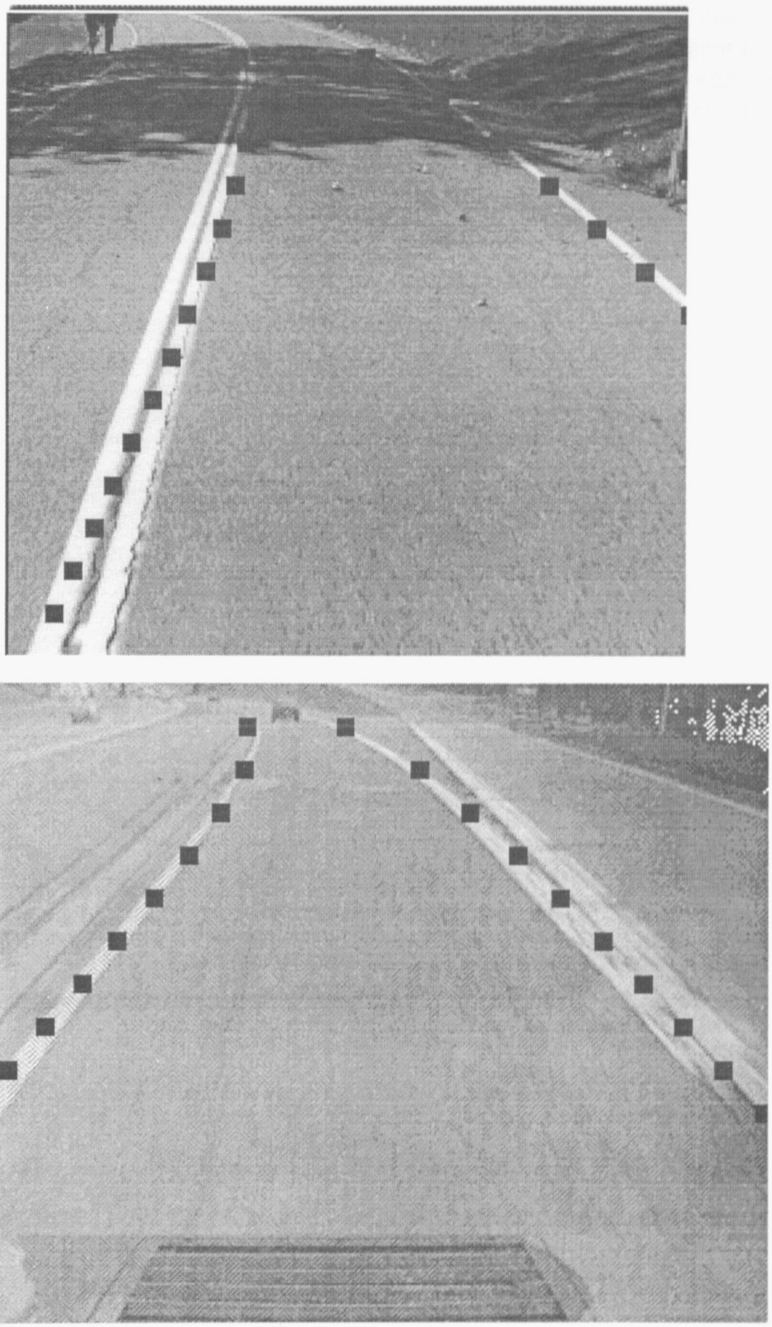
- Using the deformable template model as a prior and the matching function as a likelihood, the lane detection problem is formulated in a Bayesian setting. Locating the lane boundaries in an observed image, reduces to finding the parameters values which yield the globally maximal posterior probability density function.

The posterior density, however, is not convex with respect to the lane shape parameters—it has many local maxima. In order to escape these local maxima and find the global maximum, we employ a Metropolis algorithm (hence, the connection to LOIS Lane).

RESULTS

Shown below are three sample results of lane detection using LOIS. In each of the images, the detected lanes are overlaid on top of the original images in white dots. The poster will include several experimental results that illustrate the performance of LOIS on a variety of images. The presentation will include a video demonstration of LOIS aboard a US Army "Humvee."





IMPACT

The project has had a substantial impact on education: Several seminars were delivered—at Brown University, University of Massachusetts at Amherst, IBM T.J. Watson Research Center, and Siemens Corporate Research Center. Several papers on LOIS also appeared in print—in *Proceedings of the IEEE ICASSP-95*, IEEE IV-95, and the Springer-Verlag book (LNCS-1035) entitled *Recent Developments in Computer Vision*. These seminars and papers served to educate scientists, engineers, academics, and students on the importance of the deformable template paradigm in solving real-time computer vision problems. Several elements of LOIS are being used by team of undergraduate students who are building an autonomous golf cart to compete in an international competition. The golf cart project

provides a tremendous educational experience for the students, covering a wide range of topics—systems integration, design, vehicular electronics, intelligent control, etc. Finally, a short course on computer vision has been developed, using several elements of LOIS as examples. This course was offered to engineers and scientists at Ford's SRL in summer 1995, and is currently being offered to the undergraduate students participating under the NSF-sponsored UM-Dearborn ECE department's Research Experience for Undergraduate (REU-Site) program.

REPORT BRIEF

Development of a Low-Cost Vision-Based Tool Measurement System

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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Electrical and Computer Engineering

PARTNER John Dorset
Royal Design and Manufacturing, Inc.

ASSISTANTS J. Carpenter, B. Hornsby, A. Hughes, and J. Damron
Research Assistants

OBJECTIVE

The basic objective of the project was to develop a vision-based tool measurement system by integrating a video camera and frame grabber with existing tool measurement hardware. Software was to be written that would analyze images and provide gauging information. It also needed to be incorporated into a final production gauge for shipment to customers.

APPROACH

A video camera is used to replace the optical comparator or diode array used in traditional Royal measurement systems. A PC-compatible computer equipped with a frame grabber is used to digitize the camera signal and store it in video memory for analysis.

A number of software components needed to be written so that key features from the acquired image could be detected reliably and their locations estimated very accurately. Preliminary operations include alignment and mastering. To ensure a common reference, the tool must be perpendicular to the camera. The horizontal and vertical mastering routines, along with the horizontal alignment routine, perform this function. Once this has been done and the tool placed in the gauge, a search routine is required to find the tool. The search routine provides the information needed to move the camera so that the part is positioned correctly on the screen. The next step is to position the part for sharpest focus to maximize measurement accuracy and minimize the likelihood of multiple blobs on the screen.

Other software was written to provide any of a number of measurement operations on the tool, including determining the radius of an arc, finding extreme points, and angle measurements. In addition, routines to find the corresponding Z value for a given X value or the reverse can also be found. The following table summarizes the different routines that were written:

Routine	Description
Search	Provides guides to position the tool in the viewing window.
Focus	Focuses tool within viewing window.
V_Master	Calculates the position of a vertical edge relative to the edge of the screen.

H_Master	Calculates the position of a horizontal edge relative to the top of the screen.
H_Align	Determines the slope of a near-horizontal line.
Extremes	Finds the point on a tool closest to a specified edge.
Find_Points	Given either X or Z, corresponding Z or X returned.
Arcs	Calculates the radius of curvature for a tool's arc.
Angles	Determines the angle between two linear portions of a tool.

In order to achieve the required accuracy, gray-scale interpolation was used in most of the routines. The basic idea here is to find the approximate location of an edge using simple thresholding first. Then, a line of pixels that cross the edge are identified so that the transition from a bright region of the image (no edge) to a dark region is obtained as shown in Figure 1.

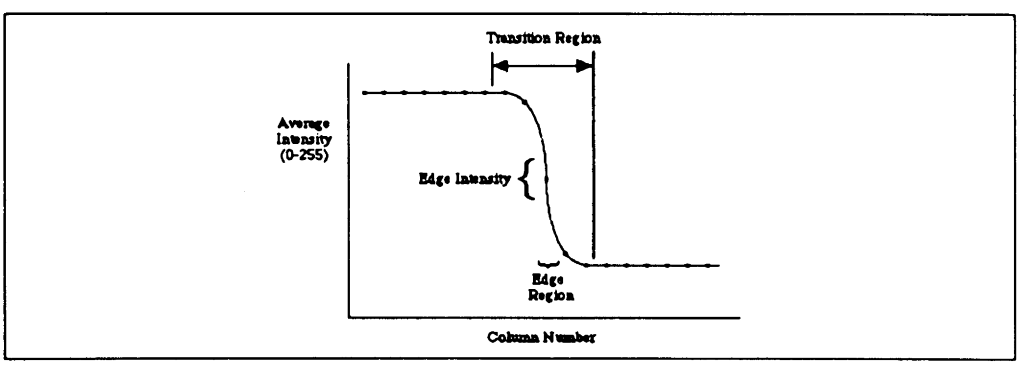

Figure 1. Transition from bright to dark regions of an image

Gray-scale interpolation is performed in the following manner. Seven dark pixels near the edge are averaged to estimate the light level in the interior of the object. Similarly, seven bright pixels near the edge are averaged to estimate the background illumination. Since a transition occurs between these two regions, the two estimates will differ significantly. The edge position is determined by the location that corresponds to the gray-scale value that is halfway between the light and dark intensities. Once the intensity value corresponding to the edge location is determined, pixels in the transition are checked for two adjacent values that bound this gray-scale value. Following this step, the difference between the bounding intensities is used to interpolate linearly the fractional distance of the edge between the two pixels.

RESULTS

By integrating vision technology with existing tool measurement systems, a significant improvement in measurement speed and accuracy was achieved. Customer acceptance has been very good and Royal has been hard pressed to meet demand.

CONCLUSIONS

Undergraduate students have successfully applied vision algorithms to a real-world application with good results. They have benefited greatly from the experience. The tool measurement systems manufacturer also has received significant benefits from this project.

IMPACT

Undergraduate student participation in the development of an advanced measurement system has provided significant benefits for the students and faculty involved and for the corporate partner. Important benefits include:

- *Excellent experience for participating students*
  The students acquired a variety of new skills, including software and integration, design of user interfaces, minimization of degradation associated with noise and nonlinear system elements, and robust coding techniques that can handle a wide variety of unusual conditions such as the presence of dirt in a given image or a poorly focused image. The students worked under conditions that were very similar to what they will encounter when working in industry.
- *Case studies for graduate and undergraduate courses*
  This project has already been used to demonstrate a number of important machine vision concepts in several courses. The basic system has already been used as a case study in ECE588, Applied Machine Vision, and will also be presented in the new undergraduate vision course.
- *Benefits for the corporate partner*
  Significant benefits have been realized by Royal Design and Manufacturing. Customer response to the new vision-based gauge has been extremely positive and demand has been very heavy, straining Royal's ability to produce an adequate quantity of gauges. There are indications from Royal that their new gauge is significantly better than competing gauges.

ACKNOWLEDGED Funding and technical support from Royal Design and Manufacturing, Inc. have significantly enhanced this project.

REPORT BRIEF

Development of a Shattered Glass Analysis System

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

AUTHORS	J. Miller and M. Shridhar Electrical and Computer Engineering
PARTNERS	V. Henry, Jack Ladewski, and J. Haywood Glass Division, Ford Motor Company
ASSISTANTS	J. Floros, A. Cunnings, S. Wortley, and B. Samuel Research Assistants

BACKGROUND

Due to legal requirements concerning specifications on tempered safety glass, destructive tests on a given number of glass panels taken from production are routinely performed. In a typical test, a glass sample is shattered and certain statistical information is manually extracted from it. Statistics, such as the particle count in regions of the panel, with largest and smallest particle sizes and length of longest shards, are commonly gathered. Unfortunately, manual counting is labor intensive and error prone and does not provide fast feedback. If a production problem occurs, a large number of finished glass panels may have to be destroyed because the problem was not detected early enough. A typical pattern is shown in Figure 1.

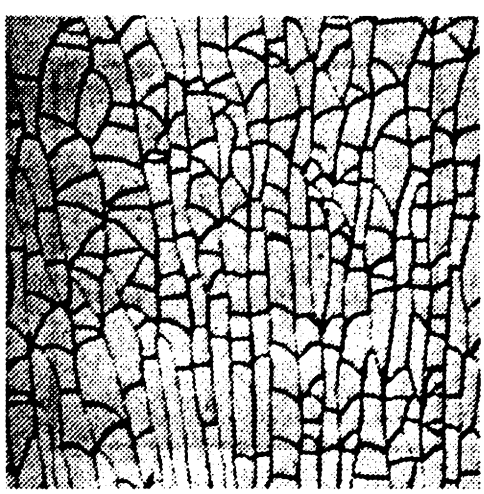

Figure 1. Typical shattered glass pattern

OBJECTIVE

The primary objective of the project was to develop an automated system for counting glass fragments. The system had to provide accurate and consistent results and be easy for plant personnel to use. This was also a good project for student participation since students would be applying advanced technology to a real-world manufacturing problem.

APPROACH

In order to develop a particle counting system suitable for production, a number of goals had to be achieved, including accurate counts, adequate processing speed, and a good user interface (which is described in the next section). The most challenging aspect of the project was obtaining accurate counts, and for this reason techniques had to be devised to suppress noise, enhance the often faint particle boundaries, and reconstruct the boundaries that were missing. In order to provide an easy means to identify the regions of interest, around each of them an orange marker is used to draw a box which will be nearly invisible in the red image from a color hand scanner but very visible in the green and blue images. After the image is captured, image processing is used to detect the particle boundaries and orange box.

Next, a background estimate of the red image is obtained by performing a gray scale morphological closing operation with a structuring element large enough to span the cracks in the image. The resulting background estimate is then subtracted from the red image to create an inverted image with the particle boundaries bright against a dark background. A fast thinning algorithm is then used to thin the image.

Once the image has been thinned, missing particle boundaries need to be restored. Each is assumed to connect to some other segment, and as such must be connected to the best candidate. Typically, two cases are encountered. In the first case, there is a section of a border missing from the middle of an edge. In this case reconstruction involves connecting the resulting two branches to each other. In the second case, a section of border is missing from the "corner" to somewhere in the middle of a piece. Because there is only one branch, it must be extended in such a way as to complete the boundary pattern. An algorithm to perform the reconstruction consists of the following steps:

1. Apply binary spatial relationship classifier.
2. Identify points with only one neighbor.
3. Locate base point, the first point along a branch that has more than two neighbors.
4. Determine direction of segment.
5. Search for other points with only one neighbor in the direction of the segment, which are designated as candidates for connection.
6. Connect any branches which have only one candidate for connection.
7. Next consider branches with multiple candidates. First, reject any candidates that do not contain the current segment as candidates for their connection. Then, connect the current segment to the remaining candidate closest to the current segment's direction.
8. Connect remaining branches to the vertex (points with more than 2 neighbors) closest to their direction, or if no vertex was found, extend the branch in its direction until the extended branch connects with the crack pattern.

At this point every segment has been completely interconnected with the particle boundaries as shown in Figure 2. It should be pointed out that the above rules only allow one connection to be made *from* each segment, but multiple connections *to* each segment are allowed. Hence, a segment can still be a candidate for another connection even if it has already been connected by a previous rule. It is this mechanism that provides reconstruction of missing vertices.

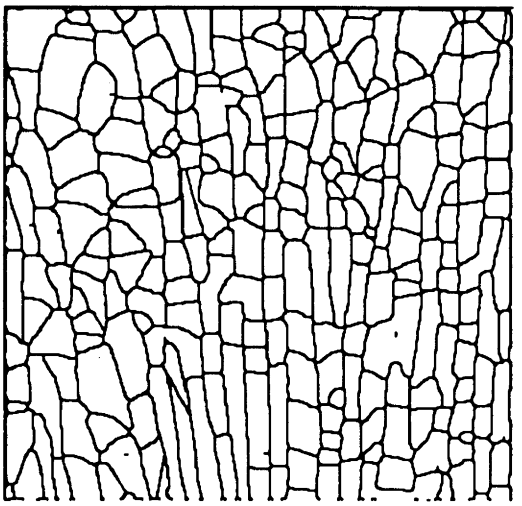

Figure 2. Image after boundary restoration

A good user interface, which is typically Windows-based for new software, was required for this software to be accepted by plant personnel. In addition, Windows was needed to control the hand scanner, so a Windows-based interface was most appropriate. Writing software for Windows applications can be a formidable undertaking given the complexity associated with this environment. After some consideration, it was decided to use Visual Basic to create the user interface since it is very well suited for this type of application.

RESULTS

The basic algorithms have been written and implemented and good results have been achieved. The software is still under development, but a recent plant trial was quite successful.

CONCLUSIONS

Undergraduate students are successfully applying vision algorithms to a real-world application and achieving good results. They are benefiting significantly from the experience.

IMPACT

Undergraduate student participation in the development of an advanced measurement system has provided significant benefits for the students and faculty involved and for the corporate partner. Important benefits include:

- *Excellent experience for participating students*
  The students acquired a variety of new skills, including software and integration, design of user interfaces, minimization of degradation associated with noise and nonlinear system elements, and robust coding techniques that can handle a wide variety of unusual conditions such as poor image quality or missing boundary segments.
- *Case studies for graduate and undergraduate courses*
  This project has already been used to demonstrate a number of important machine vision concepts in several courses. The basic system has been used as a case study in ECE588, Applied Machine Vision, and will also be presented in the new undergraduate vision course.

- *Benefits for the corporate partner*
  Significant benefits are being realized by the Ford Glass Division. Initial operator response to the new analysis system has been positive, and Ford has plans to install units in all of its glass plants.

ACKNOWLEDGED Funding and technical support from the Ford Glass Division have significantly enhanced this project.

REPORT BRIEF

Fuzzy Engineering Diagnostic Systems

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

AUTHOR	Yi Lu Murphey Department of Electrical and Computer Engineering
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BACKGROUND

The success of U. S. manufacturing industry very much depends on the quality of the product. As electronic control systems have become more advanced and sophisticated in recent years, malfunction phenomena have also become increasingly more complicated. It has been well recognized in the automotive industry that effective vehicle diagnostic systems will play a key role in the competitive market of the year 2000. In order to meet this challenge, the major U.S. automotive companies are in the process of launching an end-of-line test system at every assembly plant.

This is a collaborative research project between the electrical and computer engineering department in the School of Engineering at the University of Michigan-Dearborn and the Advanced Vehicle Technology - Core and Product Engineering (AVT-CAPE) at the Ford Motor Company. The objective of this project is to advance the technology for End-of-Line test in auto-motive assembly plants. The task performed by the End-of-Line test is fault detection and identification(FDI).

Currently, we are investigating a fuzzy model that can be used to implement a diagnostic system capable of detecting one particular type of faulty behavior. This fuzzy model provides approaches for determining control and solution variables, generating membership functions and fuzzy rules, approximate reasoning and experiment and performance analysis. The fuzzy model is generic with respect to the environment of the end-of-line test. A fuzzy diagnostic system developed under this model is expected to produce better diagnostic results, requires minimum process time, and can be easily adapted to different vehicle models.

OBJECTIVE

Diagnosis of impending or actual faults through operating data or observed characteristics of a dynamic system is generally performed by specialists who are trained in the interpretation of such patterns. The existing techniques in engineering diagnosis are largely dependent on the individual engineers' experience. There is a strong need to develop an intelligent system capable of **prompt and reliable diagnosis** for the end-of-line vehicle test. The **objective** of this project is to **advance the current technology** used in the end-of-line test. This project intends to **automate this end-of-line test so that the process is more efficient, accurate and robust**. This objective will be attained through the development of an intelligent fuzzy diagnostic system for the End-of-Line vehicle test in assembly plants.

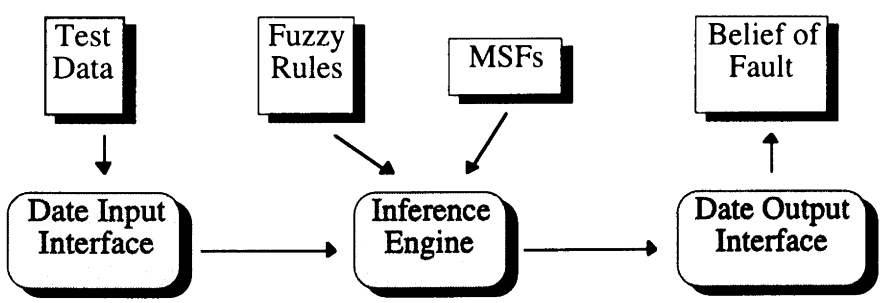
APPROACH

Figure 1 illustrates the fuzzy diagnostic model currently under investigation, where MSF stands for "MemberShip Function." The fuzzy diagnostic model consists of two major components, a fuzzy diagnostic system (Figure 1 (a)) and a machine learning program (Figure 1(b)).

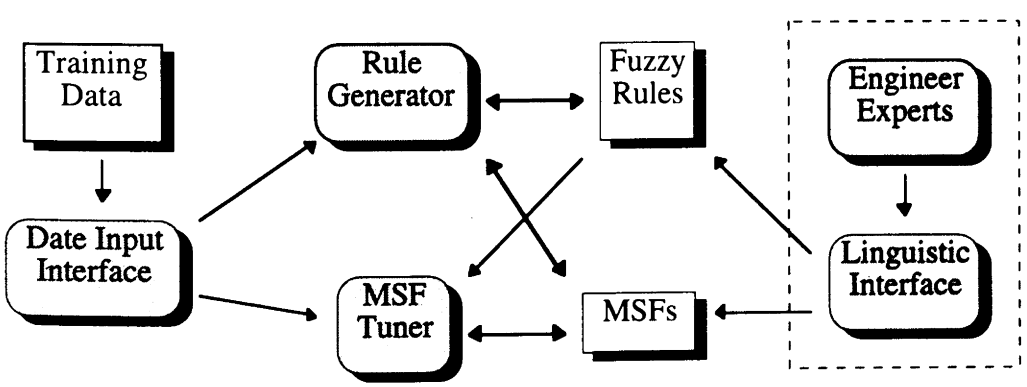
During the fuzzy diagnosis, the system reports the classification of **the solution variables** according to the values of **the control variables**. The crisp values of the solution variables are available if required. Here the solution variables are the variables that represent the type of faulty behavior that the system is responsible to detect; the control variables are the variables which give influence to the particular type of fault. For example, a vacuum leak diagnostic system has 5 control variables, Throttle_Position, Lambse_1, Lambse_2, Idle_Speed_DC, Mass_Air_Flow, and 1 solution variable Vacuum_Leak.

During the learning process (see Figure 1 (b)), the system generates the fuzzy rules and optimizes the MSFs either from engineering experts or machine learning algorithms. Therefore, the knowledge base consists of rules generated from engineering heuristic knowledge and rules generated through machine learning.

We have developed and implemented one automatic rule generation algorithm and an optimization algorithm to optimize the membership functions.



(a) Fuzzy engineering diagnosis



(b) Learning fuzzy knowledge from engineering experts and training data

Figure 1. A fuzzy diagnostic model

RESULTS

An intelligent fuzzy system has been developed and implemented for diagnosing EEC vacuum leaks and is readily transferable to the manufacturing environment. The system is

capable of learning different vehicle models and performing robust tests. Two conference papers have been published.

We have implemented the fuzzy diagnostic model to detect vacuum leaks in an electronic engine controller (EEC). We tested the system on two different types of vehicle models: Ford Thunderbird, 95 and 96 models, and the Ford Lincoln Towncar. The fuzzy learning program generated 18 fuzzy rules for the Thunderbird model and 23 fuzzy rules for the Lincoln Towncar. We tested the fuzzy diagnostic system on data sets of over 10,000 samples of both vehicle models; the accuracy of the system was above 99%.

IMPACT

The fuzzy diagnostic model can be applied to diagnosing any type of engineering fault. It integrates human intelligence with machine intelligence to give the most expeditious and accurate engineering diagnosis.

REPORT BRIEF
Real Time Video Compression

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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PARTNER	Brian Novak U.S. Army-TACOM
ASSISTANT	T. Q. Chen Research Associate

BACKGROUND

Transmission of raw video imagery from a remote vehicle to a teleoperator requires enormous bandwidths. This project investigates real-time video compression technology with high compression rate.

There is a growing need for autonomous and remotely controlled vehicle systems for a variety of missions in hostile or hazardous environments. Video transmission to command vehicles is a key technology in that teleoperation provides superior performance by applying human intelligence in path planning, obstacle avoidance, threat detection, and goal and target search. The transmission of raw video imagery from a remote vehicle to a teleoperator often requires enormous bandwidths in robotic vehicle control. Remote driving requires both a wide and deep field of view; color provides important contextual information for discriminating different objects. A wide field of view is necessary to see the path ahead, when it curves, and for medium-to-long-range terrain assessment for the path planning. In order to present enough cues for 3D information, more than 10 frames per second are required. Therefore, an effective video image compression algorithm is a key technology to the success of remote vehicle control.

OBJECTIVE

Develop high compression rate algorithms using computer vision and artificial intelligence (AI) techniques.

APPROACH

The video compression system consists of three stages. Stage 1 digitizes an incoming video signal and splits it into a color channel and a contrast channel. Stage 2 applies log-polar mapping and edge detection to the color and the contrast channel respectively. In the contrast channel, the algorithm resembles the patterns found in the so-called simple cells of the human visual cortex. Finally, stage 3 performs JPEG compression to the color channel and edge encoding. Because of space limitations, here we briefly describe only stage 2.

The Stage 2 compression has two major compression algorithms, the color image mapping and image contrast detection. The color image compression is performed by using log-polar mapping. The color image coordinates are mapped to mimic human eye-to-brain mapping, namely, retino-optic mapping from retina to brain. During the mapping, we allow the user to specify an area of focus, namely the fovea. The pixels within the fovea are not com-

pressed. The pixels outside the fovea are compressed through log-polar mapping which keeps high resolution in the center. Each mapped pixel contains three components, R, G, and B.

In the contrast channel, edge detection is performed by using eight 8x8 masks. These spatial frequency masks are used to extract texture patches resembling the patterns found in the so-called simple cells of the visual cortex. Four masks are step edges at four different orientations, namely 0, 45, 90 and 135 degrees respectively. The other four masks are pulse edges at the same four orientations. All eight masks have been implemented in hardware boards. The system applies all eight masks to the contrast channel in parallel. The outputs of all masks are compared and winner-take-all logic selects the strongest output.

In order to have effective transmission, the compressed data is classified into 4 groups according to the priority of the data:

- coordinates of the fovea center;
- edge data;
- color data inside the fovea;
- color data outside the fovea.

The program transmits the image data in the above sequence. In addition, for *color data outside the fovea*, the program uses a scan in which the samples along the innermost rings are transmitted before the outer rings. Therefore, the data stream has been sorted according to importance. The "tail" of the data stream contains the samples along the outermost rings and, if necessary, can be cut off during transmission to retain a high frame rate.

In order to optimize the transmission speed, the system eliminates the so called "invisible" samples. Figure 1 illustrates this concept. When the fovea center moves towards any corner of the screen, the farthest pixel is at the opposite corner of the screen(see Figure 1 (a)). A circle centered at the fovea with a 400-pixel long radius is much larger than the screen. After taking into account the Log-Polar mapping, we discover that at least 1/3 of the samples are invisible during rendering. However, if these samples are removed, the remaining samples will be in a non-rectangular array, and the spatial correlation will be very difficult to extract in the compression process. In order to circumvent this problem, we simply replace the "invisible" samples by the mean value of the entire image. This process significantly facilitates the subsequent compression processes.

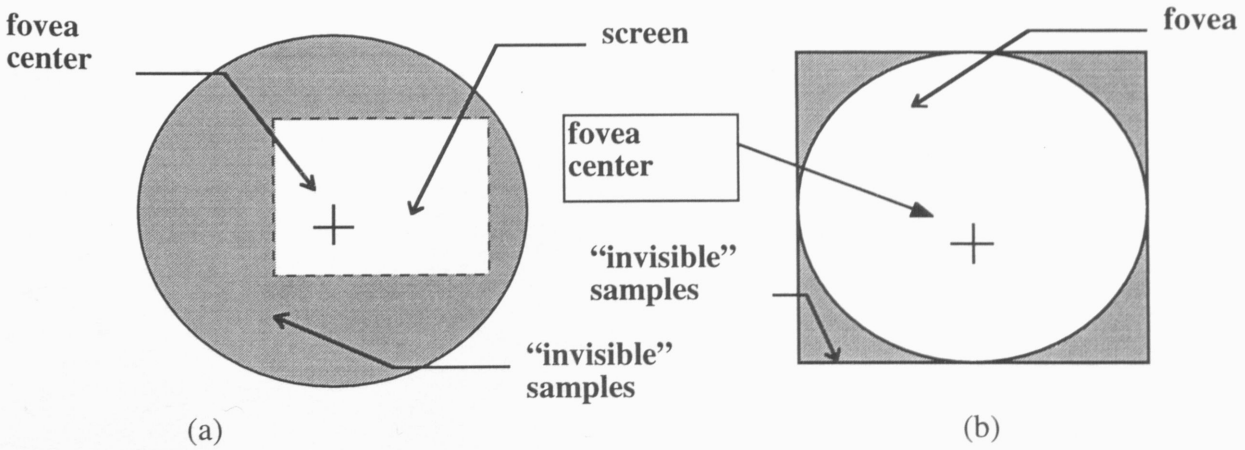

Figure 1 (a) "Invisible" samples outside the fovea. (b) "Invisible" samples of the fovea.

RESULTS

A real-time video compression system containing one video image encoder and one decoder has been implemented in multiple-processor special-purpose hardware to perform the three-stage compression algorithms.

The entire video transmission system consists of two major components, compressor and decompressor. The compressor is to be operated in the remote vehicle and decompressor is to be operated at the teleoperator. The algorithms presented above are for the compressor. The decompressor consists of the inverse operations of the compressor. The compressor and decompressor each has been implemented in separate 19 inch VME card cages containing three processors. The digitizer, log-polar mapper and edge detectors are all implemented in special hardware boards to speed up the compression/decompression process.

IMPACT

The technology developed within this project will impact in many areas that require video image transmission, including teleconference, multimedia systems, remote education and remote vehicle control.

REPORT BRIEF

Development of an Automated Check Processing System

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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ASSISTANT	Santosh Shetty
ASSOCIATE	M. Okada

BACKGROUND

The US economy has increasingly become service oriented, and current projections are that this trend will likely accelerate in both the near and long terms. Currently, checks (in a general sense) are still processed manually with intensive human participation. Efforts to automate this process have not been very successful until now; the primary reasons for this failure can be attributed to unacceptable error rates that rendered automation infeasible. Recent advances in high-speed digital signal processing and pattern recognition techniques indicate that development of check processing by machines is indeed feasible.

OBJECTIVE

The primary goal is the development of a prototype system that will extract the structure of a check and apply recognition techniques to extract relevant information (courtesy amount and legal amount) contained in these checks. It will be assumed that the orientation and/or the imaging of the check will involve translation, rotation and shearing. This implies that checks may be slanted and the camera plane may not be orthogonal to the plane of the form.

APPROACH

1) The tasks include the application of projective geometry to estimate the tilt, slant and other orientation parameters and to use this information to restore the image of the check to normal orientation. The applicant has developed a new algorithm using cross-ratios and projective geometry to model document distortion caused by scaling, translation, rotation, shearing (slant and tilt) and reflection. This new technique will be tested on check images and refined to improve overall performance.
2) Extraction of different fields in the check. This could include date field, address field, legal amount, courtesy amount and possibly bank account number. The extraction process will utilize both apriori information as well as information derived from image analysis. This phase is critical as the extraction process will have to contend with underlines, overlapping line fields, and other interference marks.
3) Application of recognition techniques to convert word images into text forms for further interpretation. The applicant has developed several recognition techniques as a result of previous funded research and proposes to adapt these techniques for word and numeral string recognition.

4) Apply contextual processing to correct any misinterpretation that occurs in the earlier stages. For example, one could validate recognition of legal amount by recognition of legal amount or vice-versa.

5) Develop a prototype system that will demonstrate the feasibility of the proposed methodologies.

6) Extend the techniques developed for general forms processing.

If one has access to a blank check image (called reference image) that has the same background as a filled-in check (called sample image) that needs to be processed, image subtraction can be a useful technique for extracting user entered information. But simple interimage subtraction is not practical because the background images of reference image and sample images are not identical. The difference between the images is caused by small changes in the parameters of the imaging apparatus as well as due to imprecise alignment of the checks prior to image capture. The authors propose a high-level interimage subtraction technique called morphological subtraction to overcome these problems and extract user-entered information.

In this method, the following realistic assumptions are made:

1) User-entered information exhibits high contrast (with respect to its neighborhood) and writing is additive.

2) Background images of the reference image and the sample image are not very different.

3) Geometrical distortion is not severe.

4) Clear reference image is available.

Component extraction procedure is performed in two parallel stages followed by a subtraction stage. An illustrative schematic diagram of the procedure is shown in Fig. 1.

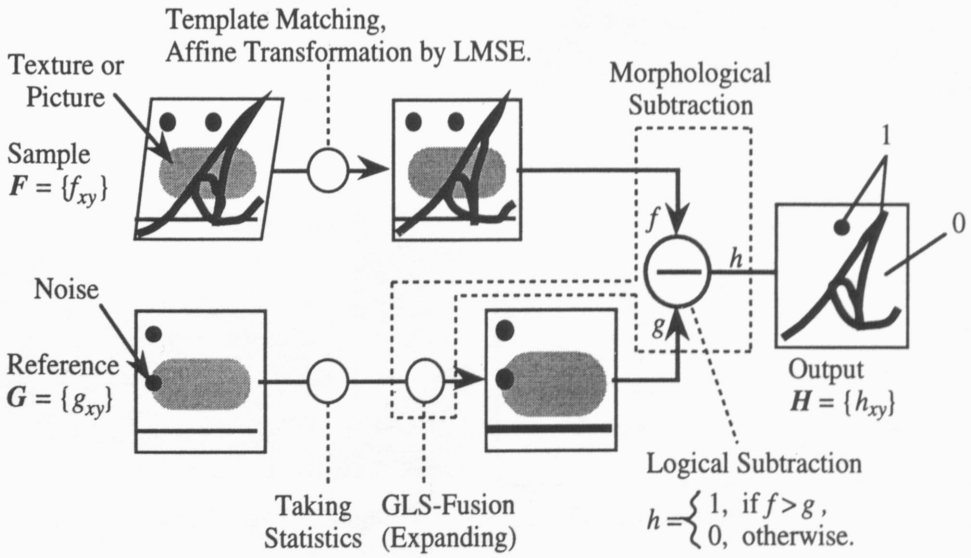

Fig. 1 A diagram of the procedure to extract handwritten components

RESULTS

The sample and reference images are gray level images that have 256 levels and are scanned with a resolution of 200 dpi. The average size of the images is about 1200x510 pixels. A pair of blank and filled-in personal bank check images are shown in Fig. 1 (a), and 1 (b) respectively.

In Fig. 1 (c), user entered components are satisfactorily extracted by the proposed method (Fig. 1 (d)). Some handwritten letters are broken by the crossing ruled lines on the check, but these can be corrected during postprocessing. Preliminary studies reveal that the extracted components are suitable for subsequent word/string recognition step. Figure 2 illustrates different stages of recognition.

IMPACT

This project will have impact on several graduate and undergraduate courses in the electrical engineering curriculum. The applicant proposes to develop several capstone design projects covering the areas of machine intelligence, image processing, computer architecture and systems integration. Modules will be developed for use in the following courses: ECE 488—Introduction to Machine Vision (a new course being developed), ECE 476—Parallel Processing, ECE 583—Neural Networks, ECE 585—Pattern Recognition, ECE 579—Intelligent Systems and ECE 588—Applied Machine Vision.

ACKNOWLEDGED

The help of the following people is acknowledged:

- Gilles Houle of TRW, who was instrumental in the development of this proposal
- Dr. M. Okada of Nagoya University, who did the initial research on this project
- S. Shetty, graduate research assistant, who is assisting the investigator in algorithm development
- Dean Sengupta for supporting the research with a grant

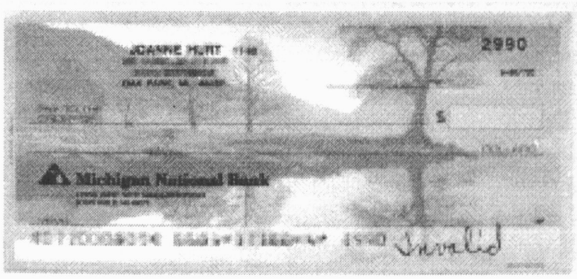

Fig. 1 (a) Blank check image for reference

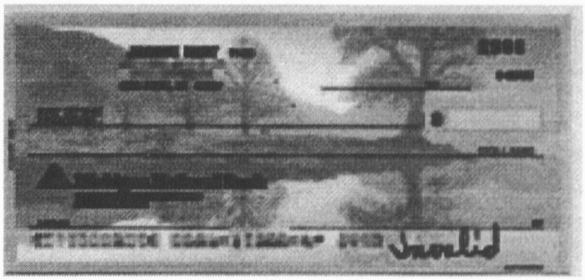

Fig. 1 (c) GLS-expanded reference image

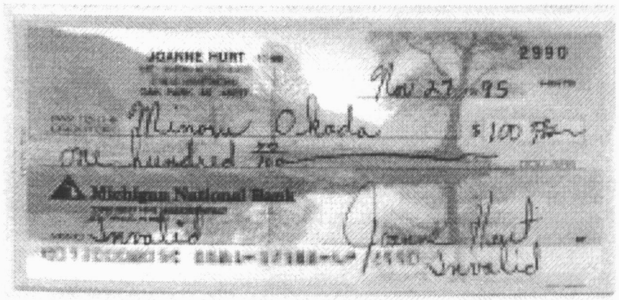

Fig. 1 (b) Filled-in check image for sample

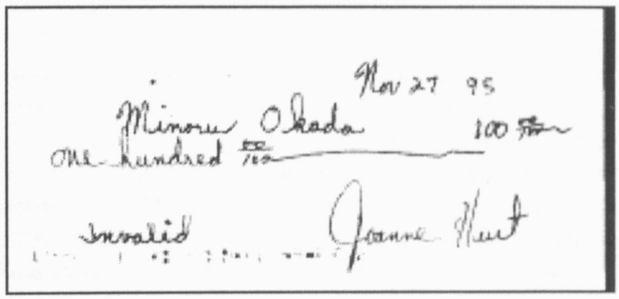

Fig. 1 (d) Extracted handwritten components

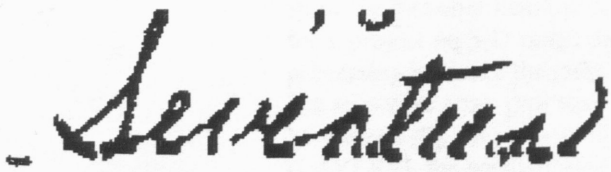

Fig.2 (a) Original Word Image

Fig. 2 (b) Slant Corrected and Segmented Image

REPORT BRIEF

Massively Parallel Processing Technology for Machine Vision

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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ASSISTANT	Xintong Zhang Research Assistant

BACKGROUND

Increased industrial automation plays a critical role in revitalizing America's manufacturing competitiveness. Machine vision is a key technology due to its potential to allow automatic inspection, process monitoring, and advanced robot guidance. However, machine vision application has not been broadly recognized due to technology limitations. One major technical limitation is the lack of high computing power that is critical in real-time applications of machine vision algorithms. Due to the nature of image processing, the lack of highly sophisticated and massively parallel processors has obscured the implementation of robust application tasks in real-time.

This project investigates the parallelism inherent in machine-vision-based industrial applications and the implementation of such parallelism on a massively parallel processor. The massively parallel processor employed in this project is the AIS-3500EX, a parallel image processor developed by Applied Intelligent Systems, Inc. of Ann Arbor, Michigan. The industrial partner for this project is Applied Intelligent Systems, Inc. (AISI). We have been encouraged by the researchers at Applied Intelligent Systems, Inc. to develop algorithms for new applications of parallel processing.

OBJECTIVE

The objective of this project is to develop parallel processing algorithms for machine vision applications in automation industry. The immediate need in our current research is the development of parallel processing algorithms for geometric feature extraction for 3-D range data. This reflects the goal of this project to introduce massively parallel processing technology to manufacturing industry. 3-D feature extraction is one of the research projects sponsored by the National Institute of Standards and Technology and one high tech company that specializes in machine vision for the automotive manufacturing industry.

APPROACH

We have collaborated with Perceptron, Inc. of Farmington Hills and applied for funding from the National Institute of Standard and Technology's Advanced Technology Program for a project on 3-D range data tools for industrial automation applications. The parallel processing is part of the tasks in that proposal. One technical option for parallel processing is a row-wise array processor exemplified by the AIS-3500EX. The tasks listed above can be potentially implemented on the AIS-series. With recent software development (LAYERS), the sophisticated parallelism can be realized through dynamic data manipulation. The major task is to develop parallel processing algorithms for primitive feature

extraction on 3-D range data. The feature extraction is one of early tasks in machine vision algorithms. The proper feature extraction from 3-D range data provides primitives for higher level machine vision tasks. The feature extraction processes include object boundary extraction, local segmentation of texture variation, regular feature identification, and gradient maps.

RESULTS

1. A new algorithm was developed for range image segmentation based on surface curvatures. The dominant points concept was extended from 2D shapes to 3D objects. The 3D surface segmentation based on morphological representations is different from the current 3D surface segmentation methods that are mainly based on assumptions of quadratic surfaces. The algorithm was developed on the AISI parallel machine.

2. Two papers related to this project were presented at Electronic Imaging '95. One was published in the 1995 Visual Communications and Image Processing conference proceedings. One manuscript has been submitted to a journal.

3. A research proposal prepared jointly with AISI will be submitted to NIST for a general competition. The topic is on massively parallel processing for vision applications on small computing platforms.

CONCLUSIONS

This project has reached two goals: (1) we applied the massively parallel processing in a few application problems and demonstrated the feasibility of using this massively parallel processing technology to solve manufacturing process automation problems and (2) we developed three new feature extraction algorithms that are novel morphological methods to solve feature identification problems.

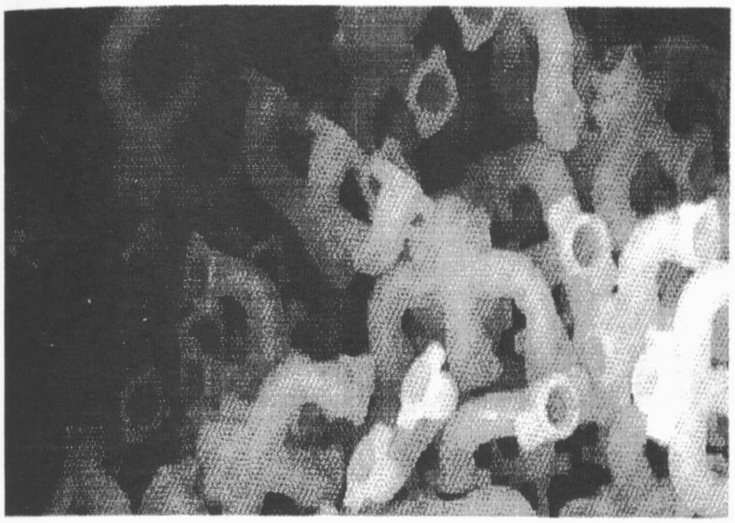
IMPACT

Machine vision applications and massively parallel processing of images are the state-of-the-art development in the areas of industrial automation. This project has had an impact in at least the following areas:

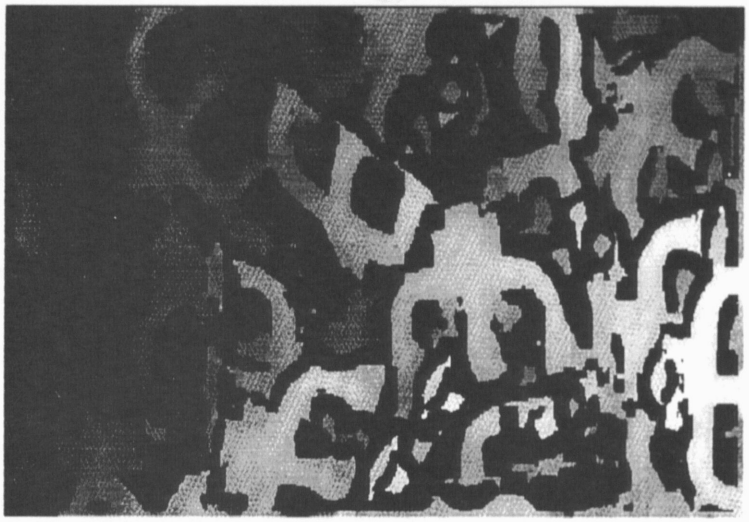
1. Faculty Enhancement: New knowledge in basic research on mathematical morphology and image analysis, and in applied research on solving industrial automation problems was gained. Collaboration with industry enabled study of the machine vision problems not only from an academic view but also from the objective of industrial application engineers. This experience will enrich the teaching material and enhance current and future research in the school.

2. Engineering Curriculum: The results from this project have been introduced in courses related to the project content. Some case studies were given to ECE 586 (Digital Image Processing) and ECE 589 (Multidimensional Signal Processing). The algorithms will be taught in other classes related to image processing and machine vision.

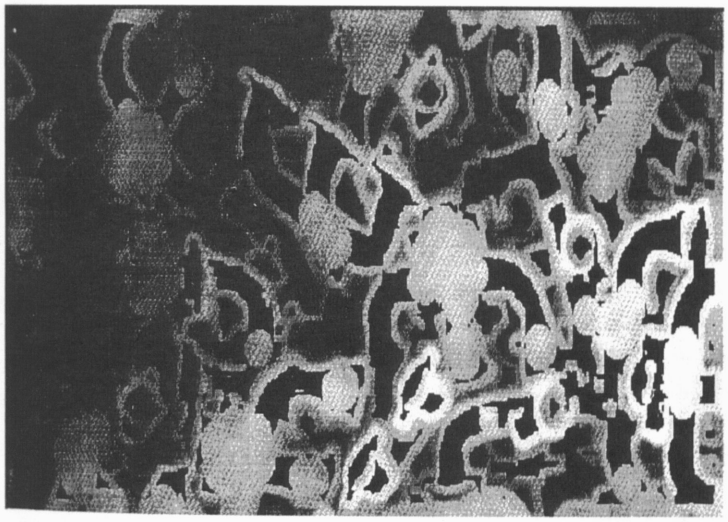
3. Participation with Industry: This project has generated some interesting results that were found useful in industrial applications. Ford Motor Company and Perceptron were particularly interested in collaborating with us to study the benchmarking problems involving real-world applications and new algorithm development for solving automation problems. Our collaboration with local industry has secured several research contracts that further enhanced the research and teaching facilities at the school, while the funding and facilities enabled us to recruit graduate research assistants in electrical and computer engineering and to provide engineering students and engineers in local industry experimental equipment and stations to pursue their interest in applied machine vision.



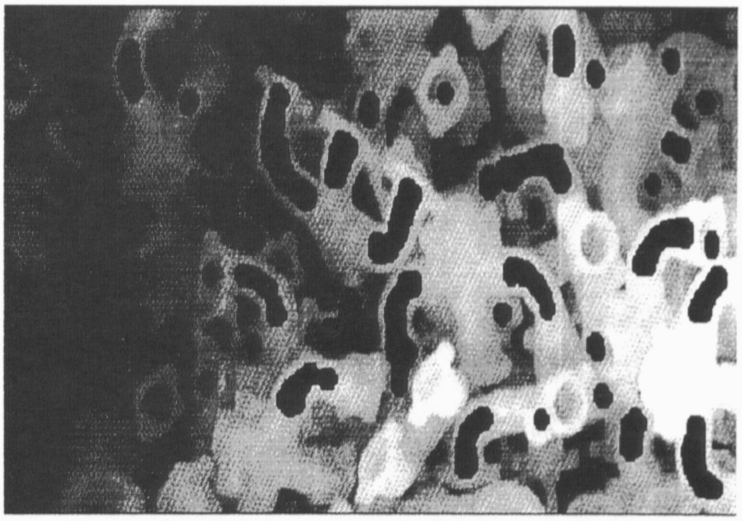
(a) Original image



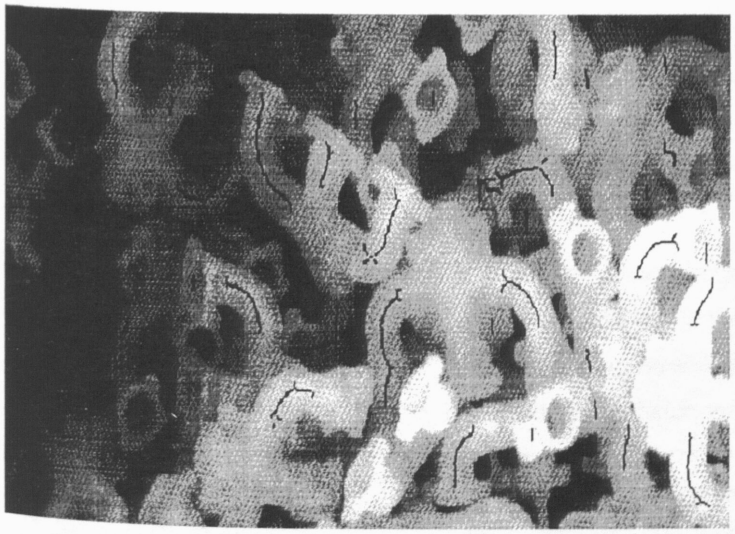
(b) After double threshold



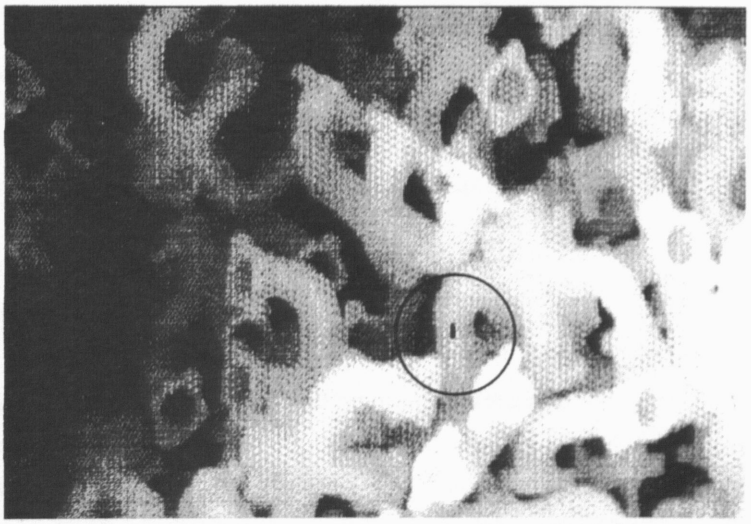
(c) Removal of background (cl)



(d) Select candidate block (op)



(e) Connectivity (skeleton)



(f) Final decision (as circled)

Example: Bin pick process. Range image (Fig. (a)) is used as the input to MPP. Algorithms are based on morphological operations. The entire process on AIS–3500EX takes 0.5 sec. Range image is taken from a laser radar imager.

REPORT BRIEF

Intelligent Monitoring and Diagnosis System for Advanced Manufacturing Systems

June 19, 1996

RESEARCH EXCELLENCE AND ECONOMIC DEVELOPMENT FUND
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

AUTHORS Yubao Chen and Elsayed Orady
Industrial and Manufacturing Systems Engineering

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Research Associate

BACKGROUND

Despite the fact that numerous advanced technologies are emerging on today's modern manufacturing shop floor, such as computer numerical control (CNC), CAD/CAM, flexible manufacturing systems (FMS), computer integrated manufacturing systems (CIMS), etc., the self-diagnosis capabilities of machine tools themselves continue to lag far behind. In particular, although many novel sensing and signal processing technologies have become available, the vast majority of today's CNC machine tools have no built-in monitoring and diagnostic function. In the absence of such a system, the shop supervisor is unable to take corrective action in the face of an impending failure of the machine tool and the manufacturing processes. The preventive/predictive maintenance on the shop floor is not completely fulfilled. Building an intelligent monitoring and diagnosis system is a significant step toward realizing the advanced intelligent manufacturing system. Intelligent monitoring, diagnosis, and control capability within the manufacturing environment plays a critical role for lowering manufacturing cost while maintaining high quality.

In light of the problems facing today's industry, we fully recognize the need for developing an intelligent condition monitoring and diagnostic system for machine tools to achieve predictive /preventive maintenance and adaptive control.

OBJECTIVE

The goal of this project has been to develop an on-line intelligent monitoring and diagnosis system that can be integrated into manufacturing systems. It should have the following features:

- Object-oriented, user-driven system
- Flexible and adaptive to variety of machines and processes in manufacturing
- Has self-learning capability
- Has intelligent decision-making capability so that human intervention is minimized

APPROACH

1) Design of the architecture of the self-diagnosis module for CNC machines

The open architecture of today's CNC machine controller makes it feasible and timely to be able to integrate a self-diagnosis module and include it as a component of the system. The architecture of such a module is designed based on the needs of machining process requirements. This system includes several function modules such as data

effectiveness has been verified in the milling, drilling, and tapping processes. The intelligent decision-making algorithm based on fuzzy logic and neural networks has been established and further improvement is still ongoing.

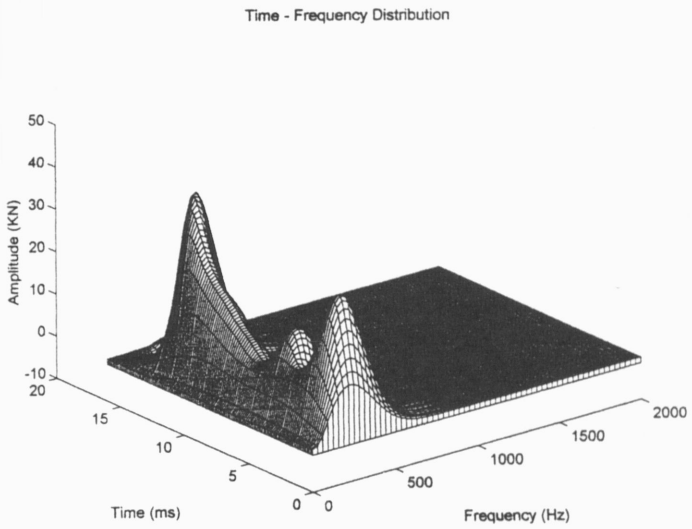

Figure 1: WVD of the signal without chatter

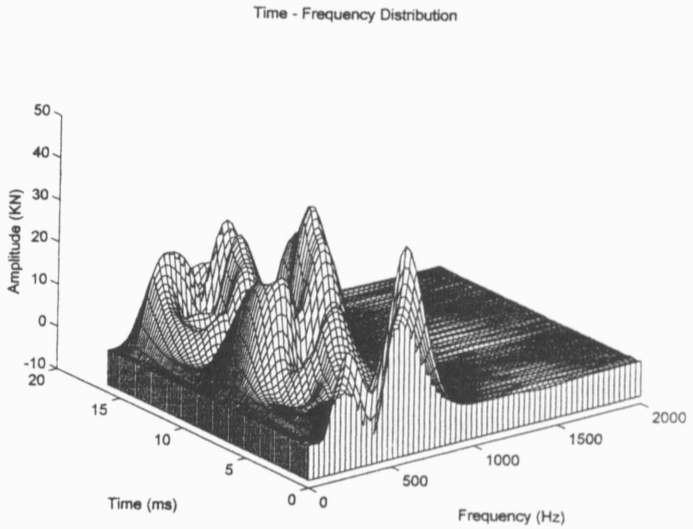

Figure 2: WVD of the signal with chatter

Figures 1 and 2 illustrate the Wigner-Ville distribution of the cutting force signal without and with chatter, respectively. The different patterns are clearly seen in these figures.

CONCLUSIONS

1) A preliminary diagnostic system for machine tools has been partly developed. Some specific features dedicated for diagnosing machining processes are included in the system.
2) Adaptive signal enhancement provides a flexible noise reduction method. No prior knowledge about the signal and noise is required. It is implemented adaptively and rapidly, so it can be easily used in industry.
3) Due to the strong nonstationary characteristic of the dynamic signal in the machining process, FFT-based spectral analysis is not always suitable. More efforts have been made to develop and apply the feature extraction algorithms that are suitable for this situation. The short time Fourier transform and the Wigner-Ville distribution have been investigated and equipped in the system.
4) Neuro-fuzzy-based intelligent decision-making scheme has been proved to be effective in diagnosis. The composite structure together with the information gain makes it flexible and accurate in application.

IMPACT

The impact of this research on industry includes:

1) A generic technology for machine tools diagnosis
2) The technology for CNC machine with self-diagnosis function
3) Improved quality and reduced cost on shop floor

This work is basic knowledge which is essential to teach to undergraduate and graduate students. The authors use this research in teaching courses such as computer-based automation.

acquisition, data pre-processing, feature extraction, intelligent decision making, and data base maintenance. Further improvements to completion of the system include adding new developed algorithms such as Wigner-Ville distribution, neuro-fuzzy-based intelligent decision-making scheme, and data base establishment and maintenance. The whole system will be verified through the CNC milling experiment in the laboratory environment and on the workshop floor.

2) Development of the advanced signal processing technologies for analyzing non-stationary signal in manufacturing process

   Considering the transient characteristics of machining processes, commonly used statistical methods and FFT spectrum are not sufficient to tackle this problem. Usually, FFT spectrum only gives the frequency components in a signal, but cannot identify the start and end of a specific component of a signal. The advanced signal processing technologies have to be developed and included in the system. Windowed FFT, or short time Fourier transform (STFT), Wigner-Ville distribution (WVD), Wavelete transform, etc., are useful in analyzing transient signals. Adaptive signal enhancement is a flexible noise reduction method and is useful in signal pre-processing. This would enhance the system for chatter detection and diagnosis, tool wear detection, and machinery performance evaluation

3) Development of a self-learning scheme for creating the knowledge base

   Statistical inference and neural network technique will be combined to form a generic scheme for knowledge learning and updating—a critical step toward eliminating human intervention. Such a capacity is missing in state-of-the-art machine diagnosis systems.

4) Development of a robust and intelligent decision-making strategy based on multiple indices

   To cope with high levels of uncertainty and noisy conditions in the manufacturing environment, a novel diagnostic decision-making strategy will be developed using multiple index voting method in associate with artificial neural network and fuzzy logic theory. The traditional single index or operator-experience-based decision scheme will be enhanced by incorporation with these advanced decision principles. The conditional probability based information gain has been used to recognize different working conditions of a tapping process and good results have been obtained. The joint probability based fuzzy information gain will be its improvement. It will be more accurate in condition classification.

RESULTS

The architecture of the system has been designed and a software shell has been developed. A prototype of a preliminary machinery diagnostic system has been partially constructed which includes the following blocks:

a) Signal sensing

b) Multiple channel data acquisition

c) Signal conditioning and recording

d) Data pre-processing

e) Feature extraction

f) Information gain weighted intelligent decision-making

Some advanced signal processing algorithms, such as adaptive signal enhancement, short time Fourier transform, Wigner-Ville distribution, etc., have been developed and their

REPORT BRIEF

Uncertainty Analysis for CMM Measurement in Quality Control

June 19, 1996

RESEARCH EXCELLENCE AND ECONOMIC DEVELOPMENT FUND
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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PARTNERS	State of Michigan and Brown & Sharpe Manufacturing Company
ASSISTANT	Songnian Li Research Associate

BACKGROUND

Coordinate measuring machines (CMMs) are becoming an essential part for the measurement of parts on today's factory floor. As the increasingly greater precision is required by modern manufacturers, CMM measurement uncertainties are becoming more and more serious, resulting in a high percentage of wrong accept/reject decisions in the quality control processes of products. Therefore, research work has been urgently needed to develop means to quantitatively evaluate CMM measurement uncertainties.

CMM measurement uncertainties are obviously affected by such factors as conflicting interpretations of the ANSI 14.5.1M Standards, lack of standardized measurement practices, and limitations of the verification algorithms. Although research work has been devoted to developing new algorithms, few of them have been proven practically applicable. Therefore, it is valuable to develop more accurate, reliable and practical algorithms for industry use. There is a need to develop new mathematical models to verify the algorithms in accordance with uncertainty.

OBJECTIVE

- Investigation and completion of uncertainty theory and criteria in relation to sampling strategy and embedded algorithms of CMM in order to quantitatively estimate and effectively minimize the uncertainty of CMM measurements.
- Testing and comparison of the algorithms currently employed by CMM manufacturers and the algorithms reported by other investigators in accordance with the minimum zone evaluation (MZE) criterion as defined in the ANSI standards.
- Development and verification of new algorithms for the evaluation of elementary geometric features.
- Investigation of the uncertainties relating to sampling strategy and software employed verification algorithms of CMMs.

APPROACH

CMM measurement uncertainties are affected by the following factors:

- CMM measurement equipment
- Data acquisition-sampling strategy
- Data processing algorithms

- Installation/environmental

The work in this project concentrated on the study of the effect of two of the four factors—data-sampling strategy and algorithms. The technical approach includes the following phases:

- Development of application model of CMM measurement uncertainty.
- Establishment of an accurate and efficient experimental system by improving experimental methods and data acquisition/processing techniques.
- Investigation of the influence of the inspection points density on the uncertainty of CMM measurement results.
- Investigation of the performances of algorithms, such as least squares method (LSM), convex hull and nonlinear optimization methods.
- Development of new algorithms using nonlinear optimization method (NOM).
- Evaluation of developed algorithms with ANSI standards as well as other common algorithms such as LSM and computational geometric approach (CGA) techniques.

RESULTS

- An experimental system has been established which consists of two CMMs programmed with DCC control software, utility software, data fitting algorithms and algorithm testing programs (ATP).
- Application models of CMM measurement uncertainty have been developed.
- The influence of sampling strategy over CMM measurement results was shown and verified through the investigation of circular and cylindrical features. Figures 1 and 2 show the effect of sampling size on the uncertainty of measurement of, respectively, the diameter and center position of a 1.5" hole. The uncertainty is determined by the standard deviation of a set of measurements. It is shown that the uncertainty decreases as the sampling size increases up to a certain limit where the uncertainty stabilizes.
- A new algorithm, using nonlinear optimization method (NOM), was mathematically defined and computationally programmed. It was verified with reported examples of other investigators as shown in Table 1.
- Evaluation results of NOM to measured data sets on differently machined parts are shown in Table 2. Corresponding results of LSM and convex hull method (CVH) are available in the table.
- It was also verified with measured data sets on differently machined parts. The results obtained with NOM were compared with LSM and CGA.
- Efficiency and convergence performances of NOM have been investigated.
- The influence of outliers over the evaluation results of different algorithms has been experimentally investigated.
- The impact of algorithms on the variety of differently machined parts, which possess various accuracy levels from coarse, such as filed parts, to fine, such as ground parts (e.g., ring masters), are experimentally tested.

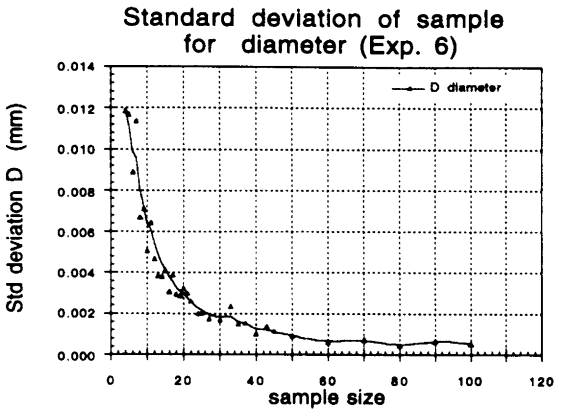

Fig. 1 Effect of sampling size on uncertainty of measurement of the diameter of a 1.5" hole

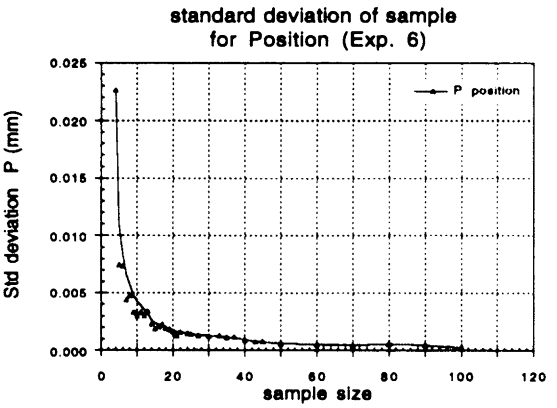

Fig. 2 Effect of sampling size on the uncertainty of the hole position of a 1.5" diameter hole

Table 1 *Algorithms Verification Results*

	Results from references			*Results of this project*	
Example	LSM	CVH	CMM	LSM	NOM
1 (15 point)	0.005377	0.005186	0.0073	0.00538	0.00519
2 (25 point)	0.001463	0.001311	0.0015	0.00146	0.00131

Table 2 *Algorithms Implementation Results*

a. *Straight Edge*

	Before filtering data sets				*After filtering data sets*		
Line	LSM	NOM (CVH)	Error (%)		LSM	NOM (CVH)	Error (%)
1	0.00925	0.00877	5.47		0.00394	0.00366	7.65
10	0.00723	0.00714	1.26		0.00186	0.00181	2.76
20	0.00800	0.00728	9.89		0.00252	0.00246	2.44
30	0.00912	0.00834	9.35		0.00813	0.00738	10.16

b. *Grinding*

Line	LSM	NOM (CVH)	Error (%)	Line	LSM	NOM (CVH)	Error (%)
1	0.00324	0.00310	4.51	15	0.00369	0.00347	6.34
5	0.00371	0.00357	3.92	20	0.00498	0.00435	14.48

c. *Planning*

1	0.04806	0.04552	5.6	3	0.06777	0.06657	1.80
2	0.04405	0.04356	1.1	4	0.06622	0.05930	11.67

d. *Milling*

1	0.04744	0.04500	5.42	15	0.04539	0.04300	5.56
5	0.04977	0.04827	3.11	19	0.04174	0.04100	1.80

e. *Filing*

1	0.02169	0.02134	1.64	15	0.04149	0.03767	10.14
5	0.02300	0.02056	11.87	17	0.04522	0.04116	9.86

CONCLUSIONS

- A sample size in between 20 and 40 points would be sufficient to have an adequate uncertainty in measuring the part diameter. However, for the determination of the center position, a sample size of 20 points would be sufficient.
- CMM measurement uncertainty is much affected by the manufacturing process. However, the sample size for stabilized uncertainty is not much affected by the method of manufacturing.
- A new algorithm named NOM has been mathematically and computationally developed and verified. The results show that it guarantees MZE as defined in ASME Y14.5.1M-1994
- The robustness of NOM is improved by taking the LSM evaluation results as initial conditions. The efficiency of the algorithm is also discussed and improved using control zone criterion to rebuild the measured data set.
- It is concluded that NOM would converge to either a global minimum or a local minimum of the objective function. Only the global minimum corresponds to MZE results as practically required. The convergence performance of NOM can be improved by locating several factors to the convergence regions determined through simulations.
- LSM always overevaluates the straightness tolerance when using it as the fitting algorithm of CMM. The overevaluation is determined by an error relative to the minimum zone value. This relative error is in the range of 0–20% for all the data sets measured on geometric features manufactured with different machining processes.
- It is experimentally proven that the data sets measured using CMM could be contaminated by outlier points, especially when the sample size is large. In this case, the straightness zone fitted with any kind of algorithm could be greatly distorted.

IMPACT

- The implementation of CMM embedded algorithm would lead to obtaining consistent results with CMM measurements that will benefit both the CMM manufacturers and users.
- The developed theory of CMM measurement uncertainty could be valuable in practice as references to quality control engineers. This may be expected for large manufacturing companies, such as Chrysler, Ford and GM, and their parts and systems suppliers, to solve several disputed problems in their quality control processes.
- The experimental results would be useful in evaluating and minimizing the uncertainties of CMM measurements.
- The research will help the project team to establish a thrust research area in the metrology field at UM-D. This will enable them to provide services to industry and attract funds from private industry.

REPORT BRIEF

A Geometric Tolerancing-Based Classification for Concurrent Design of Product and Process

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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BACKGROUND

Most efforts to enable concurrent engineering have focused on developing tools and techniques for designing completely new products. Design in many industries is evolutionary, consisting primarily of incremental changes to existing products. This category of design is the target of a new engineering philosophy called *direct engineering* (DE). While concurrent engineering is concerned with integrating people or computational design agents with traditional engineering skills, direct engineering is concerned with empowering people with new skills by giving them direct access to complete knowledge about the design and manufacturing of a part *as the part is being designed.*

OBJECTIVES

1. Group technology feasibility in RRM (rapid response manufacturing) environment and DE for concurrent design of product and process
2. Identification and analysis of part design features
3. Identification, classification, and coding of common features which have impact on both design and manufacturing of parts
4. Development of a continuous improvement methodology for product design and process feasibility

APPROACH

Feature terminology is used to define specific characteristics. From a designer point of view, the feature can be defined as a specific design functionality, whereas from a manufacturing point of view, a feature can illustrate a certain manufacturing process. In a feature-based design environment, features could be used to illustrate associativity between both design and manufacturing using "standard features." In a feature-based design system, features are defined by a set of parameters. This is known as a parametric design approach. In this approach, the designer will define a set of geometric constraints and engineering relationships that are used for creating the geometry of the object and also for establishing the associativities among the objects within the design itself. A set of expressions and variables is also used to define the dimensions of the object. When the numerical quantities of parameters are changed, the characteristics of the features are also updated concurrently. Although it is considered to be a complex approach, it will provide the necessary flexibility and increased designer efficiency by creating a new design by altering existing models.

GD&T (geometric dimensioning and tolerancing) is a technique for dimensioning and tolerancing a design with respect to actual function or relationship of the part features. This allows for a more efficient and economical approach to production. It is a major factor in controlling the quality of the part during the development of the process plan and also the production. An integrated CAD/ CAM environment requires standardization. GD&T can provide such standardization and therefore has the capability for adaptation to automation and computerization in an integrated design and manufacturing environment. Tables 1 and 2 could be used for selecting processes and machines using standard features and GD&T features.

Table 1. Sample product design features and process machine associativities

Process Features	Standard Design Features
Tapping machine	hole
Broach machine	flat face
Slotter machine	keyway
OD-Grinder machine	outer cylinder
Turn-broach machine	flat face - outer cylinder
Induction heating machine	outer cylinder - fillet - chamfer
Draw furnace machine	hole - outer cylinder - fillet - keyway
CNC lathe machine	hole - outer cylinder - fillet - chamfer - flat face
Shot Blaster machine	hole - outer cylinder - fillet - chamfer - flat face - keyway

Table 2. Sample product GD&T specified design and process machine associativities

Process Machines	GD&T Features for Outer Cylinder Tolerances(mm)					
	Size	Tolrnce	Rondns	Positn	Fnsh (m)	SRR
Polisher machine	1.6-1000	.07-.67	0-7	0-7	.1	.125-1000
Grinder machine	.5-1000	.004-0.4	.005-1000	.05-1000	.2	.25-1.5
Turn-broach machine	.2-100	.17-.47	0-7	0-7	1	.127-1007
Lathe machine	.2-1000	.04-1000	.02-1000	.1-1000	1	.127-1007
CNC lathe machine	.2-1000	.04-1000	.02-1000	.1-1000	1	.125-1000

Classification is defined as a process of grouping parts into families based on some set of rules and principles. This approach can be further categorized into the visual method (ocular) and coding procedure. The coding method of grouping is considered to be the most powerful and reliable. In this method, each part is inspected individually by means of its design and processing features. Coding can be defined as a process of tagging parts with a set of symbols which will reflect the part's characteristics. For process planning purposes, the quality of a product during design is specified by means of desired surface finishes, maximum size tolerance, geometric dimensioning, and geometric tolerance data. The amount of knowledge required for the development of routing sheets and process planning is extensive. Variant process planning is one of the techniques used in the computer-aided process planning approach. In this approach, the system takes advantage of the similarities among the components (group technology) and retrieves an existing template process plan. This template (standard plan) is stored permanently in the database and can be accessed. When the template plan is retrieved, a certain modification will be required for adaptation to the new design.

RESULTS

An extensive literature survey has revealed that very few approaches are aimed at the development of a methodology for coding and classification of parts into part families based on both design and manufacturing attributes and their conformance with DFM methodology. The developed system is used for the analysis of the engine crankshaft. Figure 1 illustrates the attributes associated with this coding system:

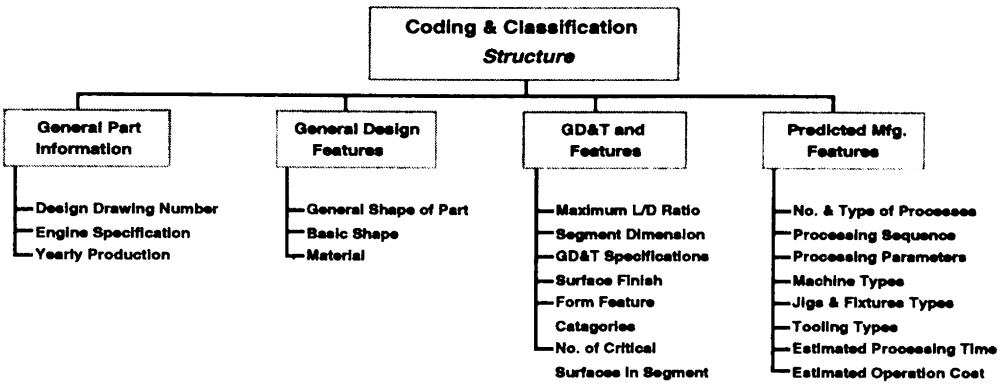

Figure. 1. The coding system structure

The coding system is developed based on the following objectives:

1. To assist the designer in data filing, design retrieval, and identification and costing.
2. To perform family identification, complexity scope analysis, primary and secondary process prediction, and costing.
3. To establish a structure for product features and quality specification, secondary and finishing process prediction.
4. To establish an environment and a structured approach to allow for manufacturability and feasibility analysis.
5. To assist the designer by providing an intelligent approach to process planning and finally CAD/CAM integration. A conceptualized overview is illustrated in figure 2.

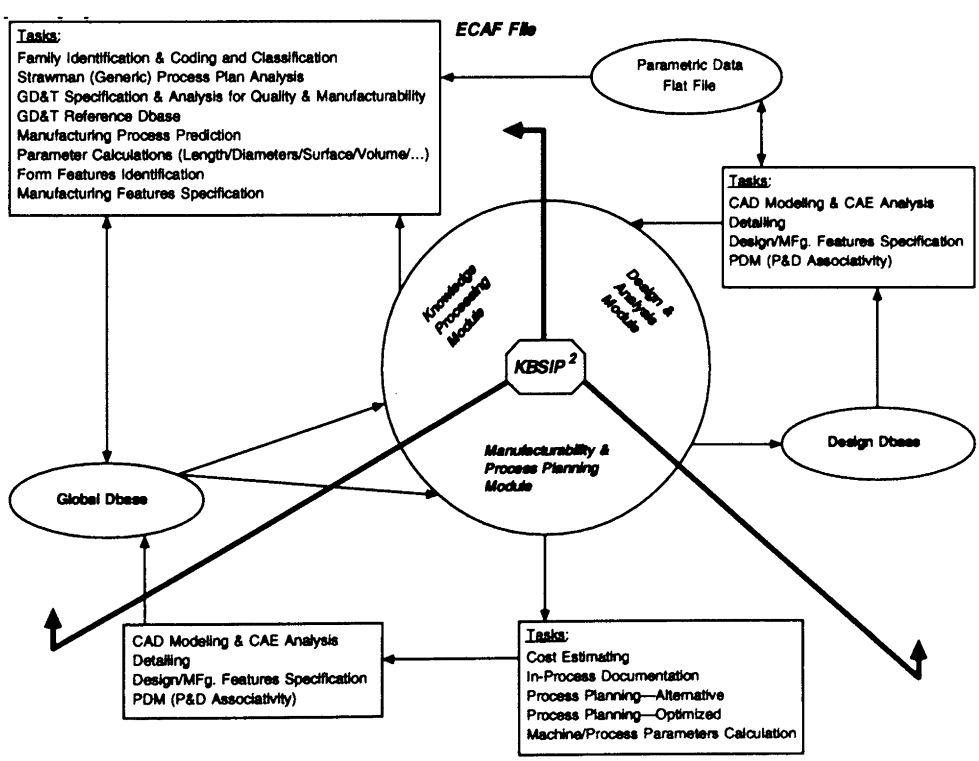

Figure 2. Conceptualized Integrated CAD/CAM Environment

CONCLUSION

The developed system is based on the variant design approach, and it clearly illustrates the major role that a group technology coding and classification system can take on within an integrated product design and process planning environment.

IMPACT

This project has had impact on three courses—IMSE 583 and 462 and EM 580. Students were exposed to the topics of GD&T and form features methodologies. Two undergraduate and two graduate students have been involved with this project. A special topic course, IMSE 499, was also offered based on this project. A series of publications has been published. A new series of courses in intelligent manufacturing and process planning is proposed and scheduled for fall 1996. The concept is being evolved for two new applications at Ford Motor Company—throttle body design and assembly and AC hose assembly.

REPORT BRIEF

Dynamnic Behavior of Composite Shafts with Automotive Applications

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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BACKGROUND

Composite material shafts can be effective in increasing the span length between bearings, reducing weight, and improving NVH (noise, vibration, harshness) characteristics of drivelines and machinery. The research addresses modeling and design of composite shafts in general applications, including those of very high rotational speed.

The modeling of composite material structures, particularly fiber-reinforced layered structures, requires consideration of various material coupling effects. In rotating shafts used for power transmission, coupling between bending and torsion occurs in common laminate configurations. Such coupling can have a strong influence on the torsional natural frequencies of the shaft and so is an important effect from a design perspective.

Another modeling issue, this one relevant to high rotational speed applications, is the influence of gyroscopic effects. These dynamic effects involve interaction between the shaft's lateral vibration and angular velocity. It is well known that the bending vibration spectrum of a high rotational speed shaft contains two modes for each single non-rotating mode. The bifurcation is due to gyroscopic effects, and the resulting pair of frequencies are known as the forward and backward precessions. Since the frequency of the backward precession is usually lower than the corresponding mode of the same non-rotating shaft, knowledge of the *rotating* shaft's spectrum is important for design in high speed applications.

OBJECTIVE

The primary objective of the research is to analytically model composite shafts for use in dynamic applications, including those of very high rotational speed. Material bending-torsion coupling and gyroscopic effects are to be included in the model, and their influences on the natural frequencies described. Also, the redesign of a production composite automotive driveshaft will be investigated using the model.

APPROACH

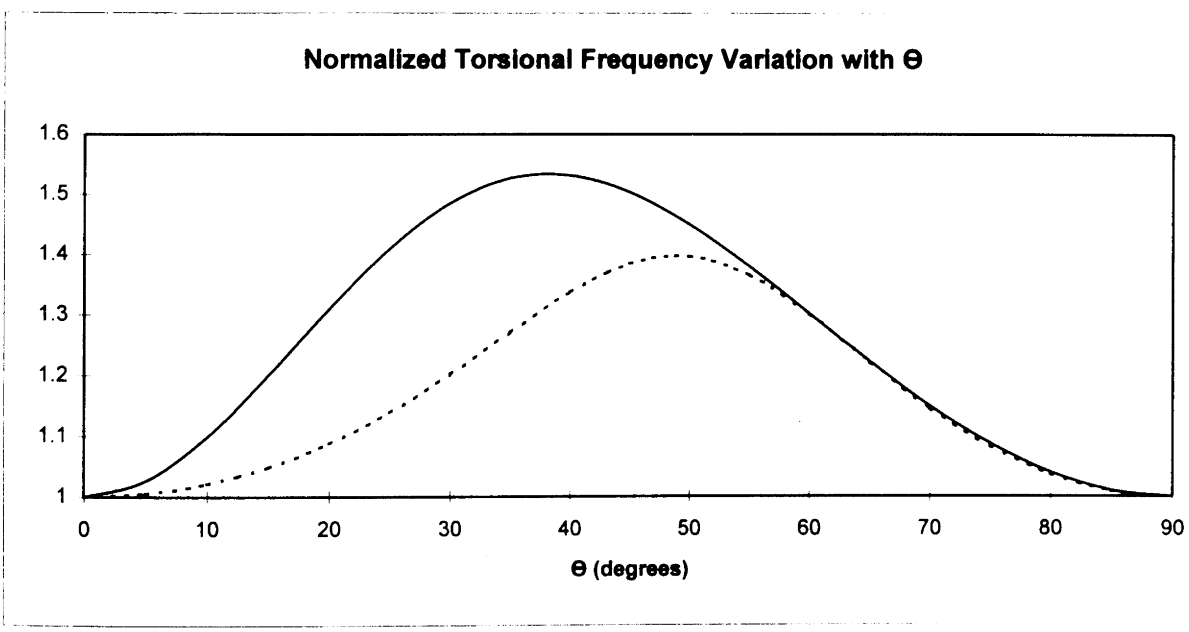
The equations describing the shaft's lateral and torsional vibrations have been derived using Rayleigh beam theory including gyroscopic effects and bending-torsion material coupling. Lamination theory is used to determine the overall material properties of a multi-layered shaft. Damping is neglected in the model and the shaft is taken to have a circular cross-section. The resulting system of partial differential equations involve the shaft's geometry, material properties, and rotational speed as parameters.

Spatial dependence in the governing equations is satisfied using Galerkin's method for pinned and clamped boundary conditions. Assuming free, harmonic vibration then yields an eigen-system from which the natural frequencies are numerically determined.

RESULTS

The figure below shows the effects of bending torsion coupling on the torsional natural frequency of a 1.3mm thick boron epoxy shaft having pinned supports and the lamination sequence 90/45/-45/θ6/90. This is a common arrangement for a helicopter transmission shaft. The graph gives the first torsional natural frequency as a function of θ for a shaft running at a normalized rotational speed of 2.5. The solid line shows the normalized frequency values predicted by the model when bending-torsion coupling effects are included, and the dashed line shows the corresponding values if these effects are neglected. It is seen that neglecting the coupling effects will result in large underestimation of the frequencies for θ between about 10 to 50 degrees.

The model has been used to explore the redesign of an aluminum-graphite driveshaft presently used in a General Motors small truck. The present production shaft consists of zero degree graphite fibers pultruded over an aluminum core. A 2mm thick graphite-epoxy shaft having the lamination sequence 45/-45/02 has been designed using trials with the model described here. Its weight is 25% less than the present production shaft, while the first torsional and bending natural frequencies are, respectively, 30% and 3% higher than those of the production shaft. Although other factors are important to the complete design of the driveshaft, such as damping, failure, cost, and ease of manufacture, this preliminary effort shows the potential advantages of carefully designed composite structural components.



CONCLUSIONS

The research has presented a model which captures the bending-torsion material coupling that can occur in laminated circular cross-section composite shafts. Numerical examples have been described in which this coupling has a pronounced influence on the torsional natural frequencies, and minor influence on the bending frequencies. This trend was observed in all numerical cases treated, however, whether or not this is generally true is left as an open question. Also, the model has been used to investigate the redesign of a composite driveshaft presently used in a General Motors Corporation small truck. Excellent results were achieved using pure graphite epoxy, and more trials are presently being explored using more practical material combinations.

In a follow-up project, static and dynamic tests will be performed on various composite shafts to validate and extend the model.

IMPACT

The analytical model can be used in an industrial design environment to assess the performance characteristics of multi-layered composite shafts for use in vehicle drivetrains. Also, it is expected that the damping characteristics of these materials can be advantageously used to reduce NVH problems which frequently occur in drivetrains.

The analytical shaft modeling ideas have been incorporated in the mechanical engineering department course ME 512 (Structural Analysis). Also, the project research has been done in conjunction with a master's thesis by J. R. Yost, and has had an undergraduate student as a research assistant.

REPORT BRIEF

Manufacturing Dependencies for Tasks, Fixtures and Dunnage Designs

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

AUTHOR	John G. Cherng Mechanical Engineering
PARTNERS	Peter Sferro, John Hamderman, and Rex Delrymple Ford Motor Company
ASSISTANT	Xin-yu Shao Research Associate

BACKGROUND

A research team was formed in the summer of 1992. The team members included Dr. John Cherng, University of Michigan-Dearborn; Dr. Richard Crawford, University of Texas-Austin; and Mr. Peter Sferro, Ford Motor Company. The mission of the team was to determine the feasibility of using a direct engineering approach to integrate the manufacturing dependencies of tasks, fixtures, and dunnage designs of a crankshaft. The results of the feasibility study were very promising. A three-year research plan titled as above was developed and funded jointly by the Ford Motor Company and CEEP.

OBJECTIVES

(1) Development of a computer model that can generate and represent the manufacturing processes of a crankshaft; (2) representation and satisfaction of geometric (feature) constraints between the crankshaft and its tasks, fixtures, and dunnage designs; and (3) integration of feature-based part design and process planning.

APPROACH

Technical approaches used are: (1) feature-based representation of crankshaft, in which the part design information is divided into the overall feature level, which contains crankshaft overall management and functional information, and the geometric feature level, which mainly consists of geometric form-features; (2) fuzzy method to determine the similarities between the current designed crankshaft and pre-existing crankshafts, the comparison process of which includes three key steps: (a) selecting comparison attributes from crankshaft feature model, (b) assigning priorities to different comparison attributes, and (c) calculating the compatibility of these selected attributes between current and old crankshafts; (3) case and knowledge-based process design method, in which, on the basis of comparison results, the most similar crankshaft will be selected as the case part for variant process design (if no similar part is found or the variant method can only fulfill part of the design work, the knowledge-based generative method will be used); and (4) multi-level program strategy for process generation, which includes six levels of simulations, (a) select the manufacturing methods, (b) generate operations and sequence, (c) select manufacturing machines and cutting tools, (d) determine cutting parameters, (e) integrate fixture and dunnage designs, and (f) complete total optimization.

RESULTS

1. The system structure of integrated part feature modeling and process planning was completed as shown in Figure 1.

2. A dynamic tree data structure for describing part information was designed and completed.
3. A Windows operation-based part feature modeling environment was developed as shown in Figure 2.
4. A crankshafts fuzzy comparison module for variant process design was developed. Figure 3 presents a typical comparison result of crankshafts.
5. A prototype sub-system of case-based process design was completed. Figure 4 implies the dynamic structure for representing process plan from summary report to detailed manufacturing parameters, which includes edition functions, such as Add, Delete, Save, Save as, etc.
6. Several knowledge bases such as operation selections, machine tool selections, and sequencing were established.
7. The accesses to ORACLE database and Microsoft EXCEL were established.
8. A network flow method for process optimization has been designed.

CONCLUSIONS

1. Design-with-feature method is suitable for modeling complicated mechanical parts and provides the possibility of integrating part design and manufacturing process design.
2. Fuzzy logic method can be employed for practical and intelligent comparisons.
3. It has been proven that significant time saving as well as quality improvement can be achieved by using the variant design approach, because it applies manufacturable part design and process planning information.
4. The key issue for realizing rapid response manufacturing or concurrent engineering is to provide engineers the direct access to complete knowledge of design and manufacturing during every stage of part design.

IMPACT

It is believed that the concept developed from this project can be easily adopted to other manufacturing processes as well as other industry fields. These technologies and concepts can be integrated into our engineering curriculum, such as the undergraduate design courses ME425, ME464, ME381, and ME481 andm the thesis topics of the graduate program. The software developed is under improvement at Ford for part and process design. Last year, one master's degree student graduated from the Industrial Operations Engineering Department, University of Michigan, Ann Arbor. He was a graduate student research assistant supported by this project. Currently, one Ph.D. graduate student from Huazhong University of Science and Technology, P. R. China, is involved as a graduate research associate in this project.

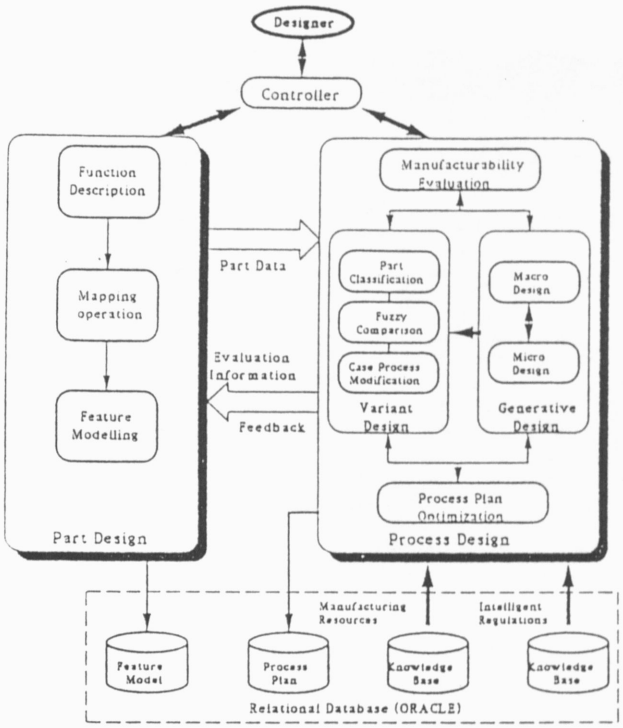


Figure 1. System Structure of Integrated Part Feature Modeling and Process Design

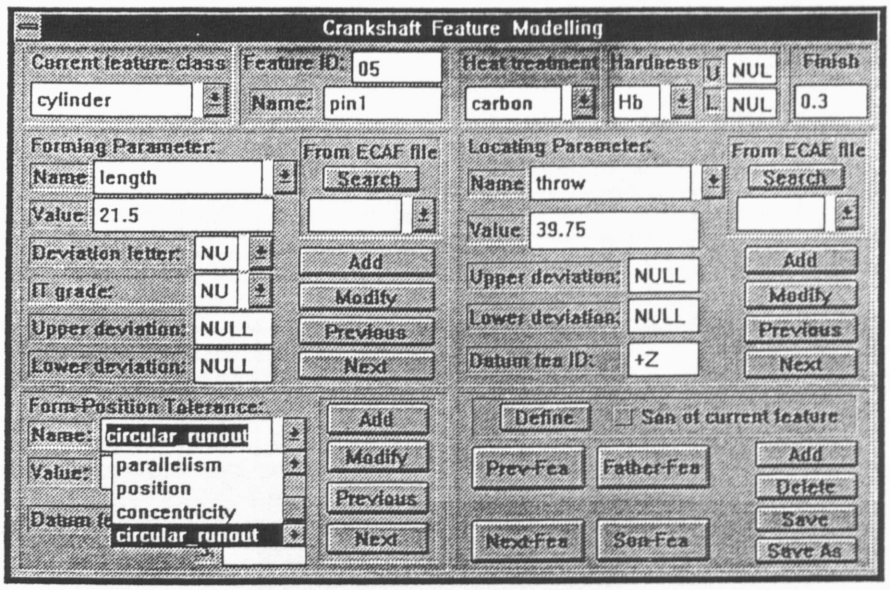


Figure 2. Crankshaft Feature Modeling

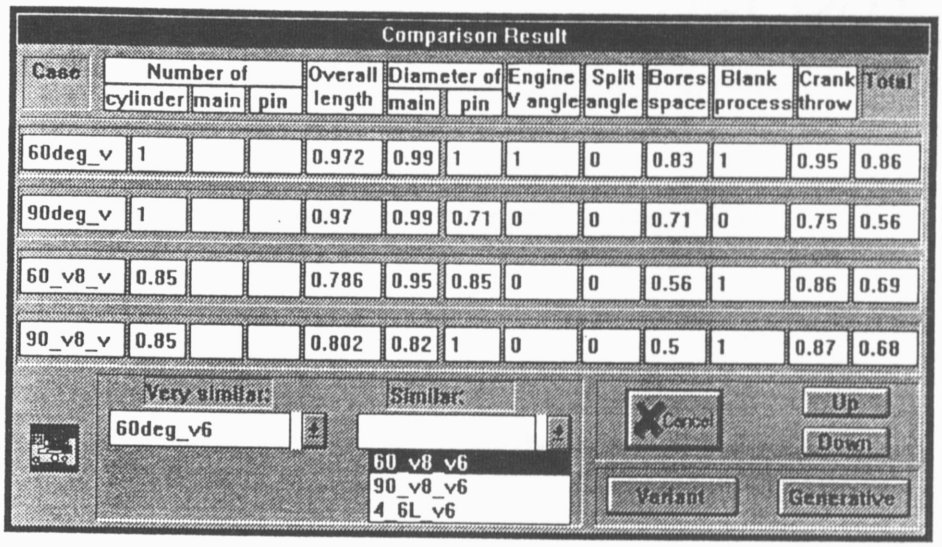


Figure 3. Comparative Study for Variant Design

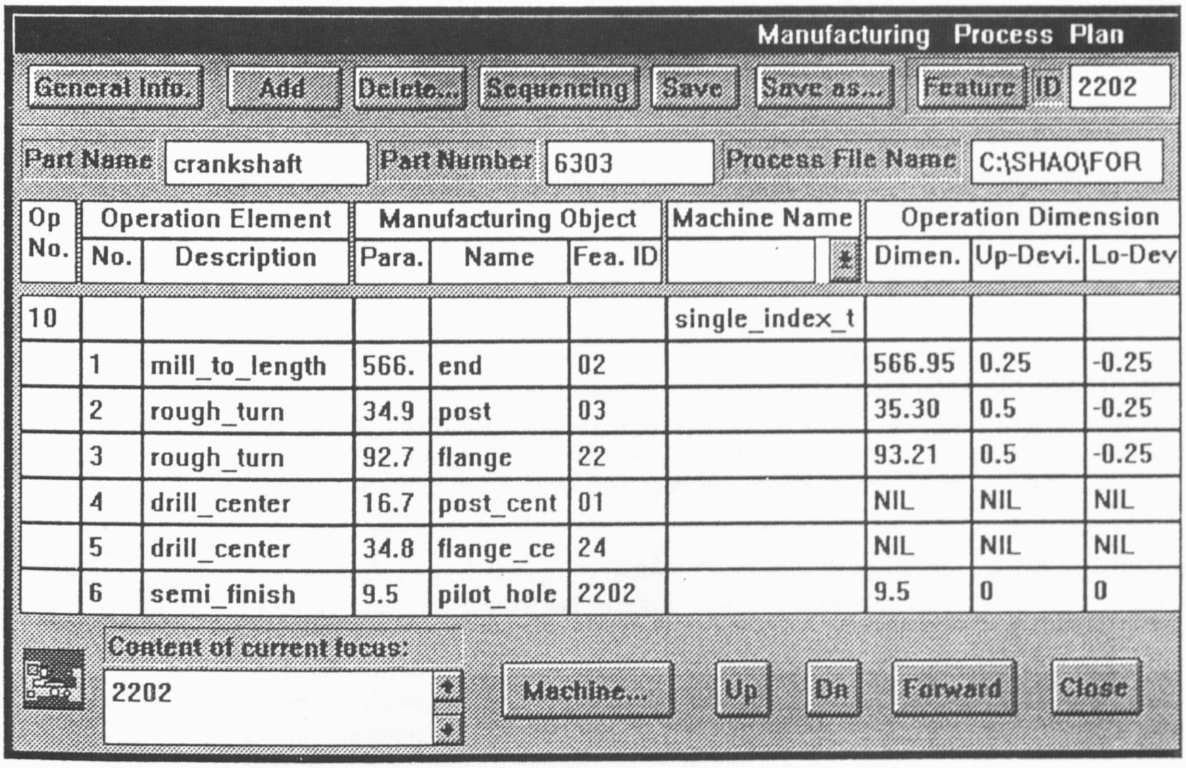


Figure 4. Window for Process Generation and Edition

REPORT BRIEF

An Elastoplastic Damage Coupling Analysis for Crashworthiness of Aluminum Tubes

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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PARTNERS	Shen Wu, Hari Agrawal, Matthew Huang, Omar Faruque Ford Motor Company
ASSISTANT	Fan Yang Research Associate

BACKGROUND

Strong interest in producing lightweight car bodies has prompted the need to use aluminum materials as an alternative. Application of aluminum material, however, should be accomplished without sacrificing the crashworthiness and crash energy management of the vehicle structure. To this end, better understanding of the performance aspects of aluminum structure under crash loading conditions is necessary.

OBJECTIVE

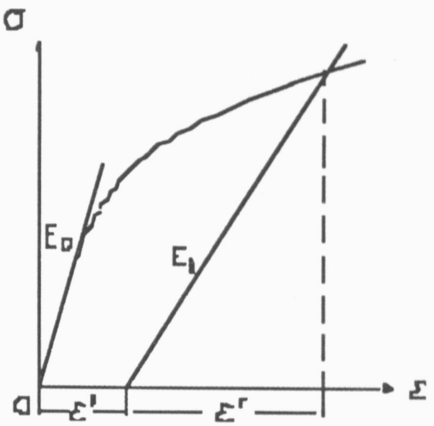
The primary objective is to develop a methodology for aluminum structures capable of accurately describing and quantitatively predicting prior- and post-collapse nonlinear behaviors due to material damage and other related crash characteristics that are essential to the integrity and safety of vehicle structures.

APPROACH

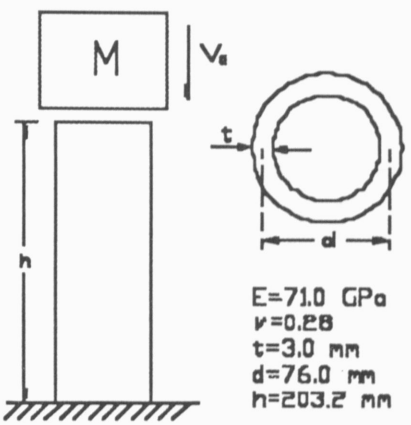
The approach is based on a state-of-the-art technology known as the theory of *damage mechanics*. Based on the thermodynamics of irreversible process and the internal state variable concept, the theory employs appropriate mechanical variables to model the damage state and then formulates their evolution equations to describe the progressive response of the damaging material. This theory can take into account the degradation of material properties at the microstructure level to be analyzed with continuum mechanics theory.

RESULTS

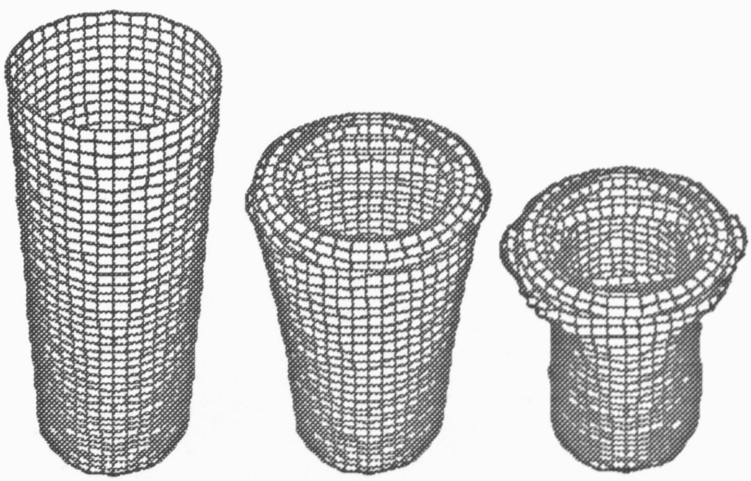
The newly developed damage mechanics theory capable of covering the entire deformation range, including reversible and residual ones, has been implemented in a general-purpose explicit nonlinear finite element code. The effects of damage due to the growth of micro-voids and micro-cracks are included through the introduction of a series of internal state variables. These variables represent degradation of elastic moduli as well as influence of plastic behavior of the materials. The finite element program can be used to analyze aluminum structures subjected to complex service loading conditions and identify associated failure locations to assess crash-worthiness. The verification and usefulness of the damage model has also been demonstrated by characterizing axial crush of an aluminum thin-walled cylinder. As most structures contain some degree of manufacturing defects, a fraction of geometrical imperfections in the cylinder has been introduced to more realistically describe a real-life structure. A satisfactory agreement between the results of finite element crash analysis and tests has been achieved.



Coupled elastoplastic damage model

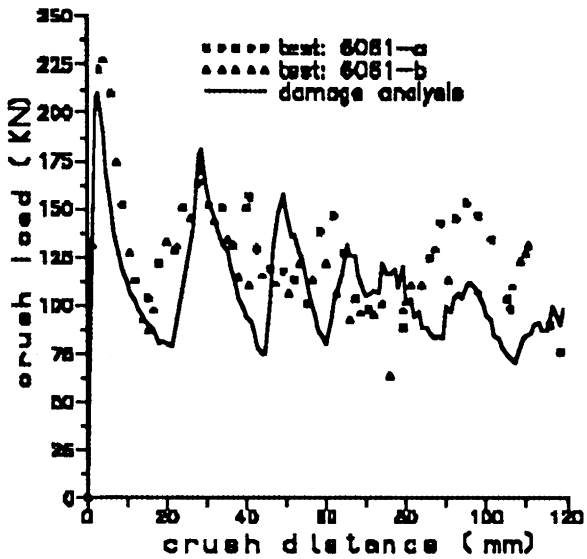


Axial crush of aluminum circular tube



(a) (b) (c)

Crushing of aluminum circular tube
Crushing distance (a):0mm; (b):49mm; (c):79mm



Crush load vs. crush distance

CONCLUSIONS A damage analysis for crashworthiness of thin-walled aluminum cylinders has been satisfactorily developed. The method of analysis can be used to effectively analyze crashworthiness performance of vehicle structural components.

IMPACT The theory of damage mechanics has not been taught as a subject in either undergraduate or graduate courses. An attempt will be made to introduce it, for the first instance, in a graduate-level course. On the industrial side, a research proposal has been submitted to Ford Motor Company for damage characterization of aluminum vehicle structures in terms of crashworthiness and crash energy management.

REPORT BRIEF

Control of Dimensional Variability in Injection Molded Plastic Parts

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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ASSISTANT	Zhouxuan Xia Research Assistant

BACKGROUND

Dimensional variability in injection molded plastic parts is a common occurrence in the plastics industry. The principal source for this variation is the mold shrinkage. In a multi-cavity mold, the variability can be cavity-to-cavity type as well as run-to-run type even when the parts are molded under the same processing conditions. If a product is assembled using different parts, the dimensional variations in the parts can create uncertainty of physically matching them in the assembly line. This may require frequent adjustments in the assembling operation which, in turn, can reduce the productivity by slowing down the automated assembly process. There may also be a higher rate of rejection of parts that could not be assembled easily. In any case, the production cost will be increased.

OBJECTIVE

The objectives of this project are (i) to investigate the cause of dimensional variability in small thermoplastic parts injection molded in a multi-cavity mold, and (ii) to recommend ways to reduce the dimensional variability in these parts. The part selected for this investigation was an iso-relay base, which is one of the components in a relay used in the automotive lighting system.

APPROACH

An experimental approach was used in the first half of this project. The second half of the project, which is just being initiated, will involve injection molding simulation using C-Flow. The purpose of the simulation study is to verify the experimental results as well as to generate a theoretical understanding of the dimensional variability problem.

Injection molding experiments were conducted in a 90-ton Toyo injection molding machine. An 8-cavity production mold was provided by United Technologies Automotive.

The cavities were numbered 9 through 16 in the mold. The material for the iso-relay base is a 33 weight percent short E-glass fiber reinforced nylon 6,6, which was supplied by DuPont. Two different types of experiments have been performed:

a) Short shot study to investigate flow of the material in the runners as well as into the cavities.

b) Injection molding study to investigate the variation in shrinkage with mold temperature, hold pressure and shot size as the principal process variables. The outer dimensions of

each molded part were measured in the flow (L) and cross-flow (T) directions and compared with the nominal mold dimension of 27.9 mm to calculate shrinkage.

RESULTS

Following are the results of the experimental study conducted so far:

a) The short shot study has indicated that the mold is not balanced and the outer four cavities are filled later than the inner four cavities. This means that the inner cavities are packed more than the outer cavities, which can be a source of differential shrinkage in a semi-crystalline polymer, such as nylon 6,6.

b) Fig. 1 shows the variation in the L- and T-direction shrinkages in cavity number no. 9 over a total of 30 consecutive runs. Similar data were obtained for all cavities in both L and T directions at all the molding conditions investigated. The results of the shrinkage measurements are summarized below:

   1) The T-direction shrinkage is higher than the L-direction shrinkage.

   2) In general, a higher mold temperature at a given hold pressure or a higher hold pressure at a given mold temperature produces a higher shrinkage.

   3) However, the average run-to-run shrinkage is reduced at higher mold temperature and higher hold pressure.

   4) No particular trend was observed to conclude on the effects of mold temperature and hold pressure on the cavity-to-cavity shrinkage variation.

CONCLUSIONS

a) For equal flow into all cavities in a multi-cavity mold, it is very important to ensure that the mold is balanced; otherwise, there will be unequal packing, which may contribute to unequal shrinkage and cavity-to-cavity dimensional variability.

b) High mold temperature as well as high hold pressure tend to reduce the run-to-run dimensional variability

IMPACT

a) The results of this study can be applied directly to reduce the dimensional variability in the iso-relay base. More importantly, this study has demonstrated the usefulness of establishing the optimum process parameters at the prototyping stage so that fewer problems will occur later in production or in assembly.

b) The results of this study are being prepared for publication as a technical article and will be used as a case study in the undergraduate plastics and composites manufacturing course (ME 484).

c) The injection molding simulation study will be used as part of a Ph.D. thesis by a graduate student in mechanical engineering.

ACKNOWLEDGED

Acknowledgment is due to United Technologies Automotive, Toyo, Maruka Machinery Co., Conair, and DuPont for their support on this project.

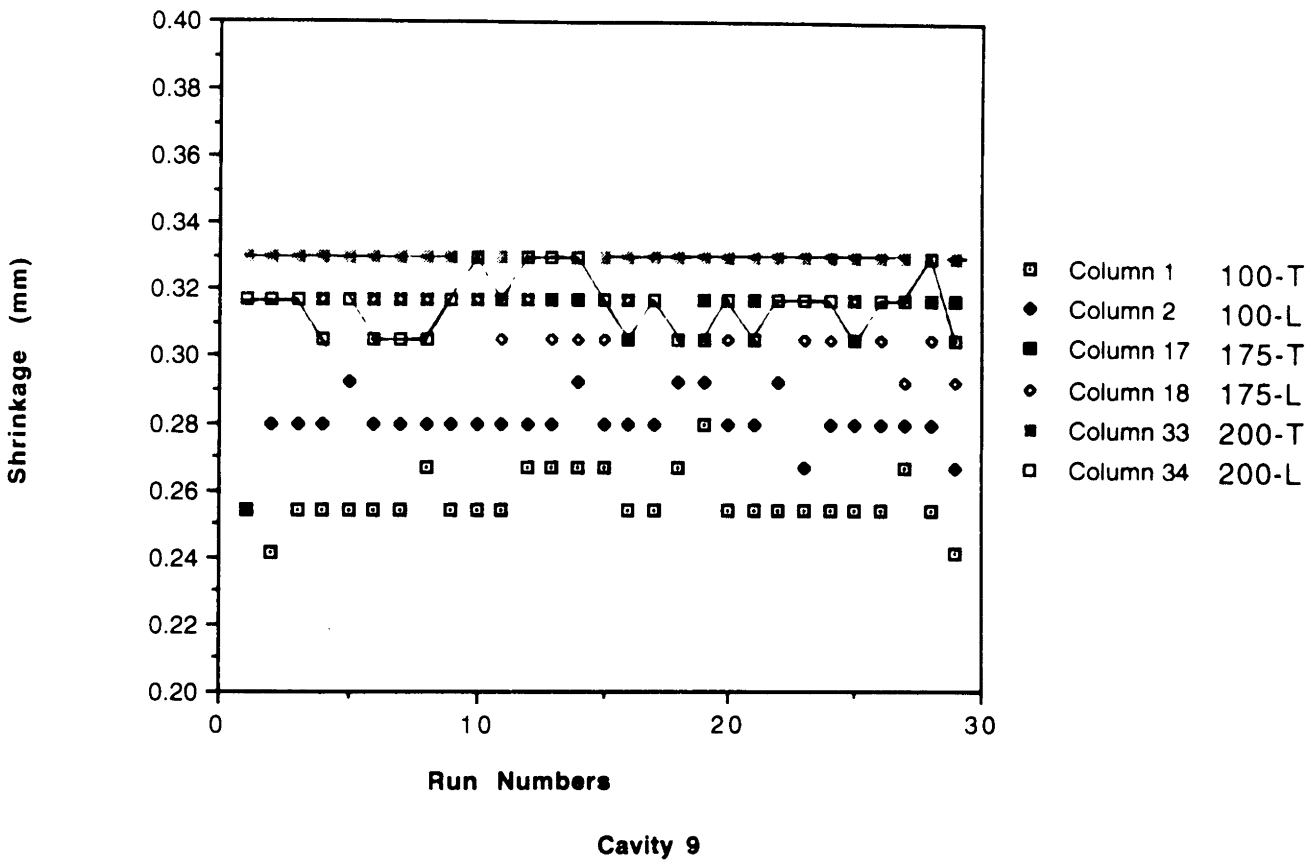

Fig. 1: Variation of shrinkage in the L and T directions in Cavity no. 9

REPORT BRIEF

Development of Fatigue Resistant Joints for Automotive Applications

June 19, 1996

MICHIGAN MATERIALS AND PROCESSING INSTITUTE (MMPI) AND
AUTOMOTIVE COMPOSITES CONSORTIUM (ACC)
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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PARTNER	Jessica Schroeder General Motors
ASSISTANT	Sanjay Mazumdar Research Assistant

BACKGROUND

Automotive manufacturers are currently employing sheet molding compound (SMC) and structural reaction injection molded (SRIM) composite parts to replace sheet metal body parts. In such applications, joining of materials will be quite crucial. It is well known that, for metals, fatigue is the major cause of structural failure and many fatigue failures are associated with some type of joint. Although the fatigue-to-static strength ratio is better for composites than metals, it is still necessary to have a detailed understanding of the behavior of joints in composites as well as combinations of metal and composites. In the literature, most of the research is done on static tests of adhesive and bolted joints. The design of composite joints in automotive applications should not be based on static test results only, since many automotive components experience vibrations and variable loads, both of which may lead to fatigue failure. There are no standard guidelines available to-date for designing against fatigue failure of joints between automotive composites and metals. Hence, a comprehensive study is required to provide an understanding of the factors controlling the joint strength, to generate data on the strengths to be expected from a particular design, and to assist in producing improved joint designs with consequent gain in joining efficiency.

OBJECTIVE

1. Determine the effects of joint parameters on static and fatigue strengths of joints.
2. Perform finite element analysis (FEA) of joints and validate the experimental results with finite element (FE) results.
3. Study the fracture surface to understand the failure behavior.
4. Develop design guidelines based on FEA and experimental results to design and build real structure.
5. Determine the effect of moisture absorption on the joint strength.

APPROACH

The proposed research program utilizes experimental and theoretical approaches to develop useful joint configurations and joint design guidelines that can be implemented in practice. SMC and SRIM plates were supplied by the Automotive Composites Consortium (ACC). These plates were cut in the desired configuration and adhesively bonded using B.F. Goodrich Exp 654-G epoxy (supplied by ACC). Standard specimens were prepared according to ASTM D1002. Many different specimen configurations were also explored.

Static and fatigue tests were performed in a computer controlled MTS machine. Finite element analysis of a single lap bonded joint was performed on a Sun Sparc workstation using ANSYS software.

RESULTS

Over a period of one year, static and fatigue tests were conducted on SMC-SMC and SRIM-SRIM adhesively bonded joints. Effects of design parameters such as lap length, adhesive thickness, taper angle and recessing on the performance of these joints were investigated. Microscopic study was performed to analyze the failure surface. The results are summarized below. For brevity, only the most important results on SMC-SMC are shown in Figs. 1-4.

SMC-SMC bonded joint:

1. Effects of surface preparation and cross-head speed on the load carrying capacity of SMC-SMC adhesively bonded joints are studied. In the cases of dry cleaning and acetone cleaning, the peak load increases by about 30% for the increase in cross-head speed from 0.05"/min to 1.0"/min.
2. The load carrying capacity first increases with an increase in adhesive thickness from 0.005" to 0.013" and then decreases with further increase in adhesive thickness for SMC-SMC bonded joints (Fig. 1). Adhesive failure was found to be the dominant failure mode in lower thickness range (0.005" to 0.013") and fiber tear is found to be dominant above 0.03" adhesive thickness.
3. Design of experiments (Taguchi method) was performed to see the effects of lap length, adhesive thickness and taper angle (Fig. 2).
4. Effects of lap length and adhesive thickness on the fatigue strength of the SMC-SMC bonded specimens were investigated (Fig. 3). It was found that the fatigue load increases by 37% for the increase in lap length from 0.5" to 1.5". With the increase in adhesive thickness from 0.03" to 0.05", the fatigue load decreases by 14.5%. The fatigue strength at 3×10^6 cycles is approximately 50% of the static strength.
5. The shear stress distribution across the adhesive thickness, determined by FEA, is found to be non-uniform. The shear stress distribution across the mid-thickness of the adhesive is shown in Fig. 4.

SRIM-SRIM bonded joint:

6. SRIM-SRIM bonded joints provide higher bond strength compared to SMC-SMC bonded joints with the same adhesive described above.
7. SRIM surface is found to be very rough compared to SMC surface. This roughness creates mechanical bonding at the joint interface and has significant effect on the joint strength.
8. A comparison of joint strength between the dried and as-received SRIM specimens shows that the drying of SRIM specimens prior to adhesive bonding improves the load carrying capacity.
9. The fatigue load at 4×10^6 cycles is estimated at 45.9% of the static load for dried SRIM specimens with 0.5" lap length and 0.03" adhesive thickness.
10. Effect of moisture on static strength of SMC-SMC and SRIM-SRIM bonded joints is found to be insignificant.

IMPACT

This project has significant impact in the following areas:

1. With the knowledge gained from this project, real structures for various automotive applications (such as joining of automotive truck boxes, attachments, cross members, etc.) can be designed and built more efficiently.
2. During this project, the relationship between joint strength and joint parameters such as lap length, adhesive thickness, substrate thickness, etc., in the case of adhesive bonding and washer diameter, hole size, thickness, edge distance, etc. in the case of bolted joints will be generated. This relationship will provide design guidelines and prediction tools for designing against static and fatigue loading.
3. Fatigue resistant joints and hardware (washer, inserts, etc.) generated during this study will prolong the life of structures.
4. One undergraduate mechanical engineering student conducted research on various joint configurations for this project.
5. The work so far will be published in three separate technical articles.

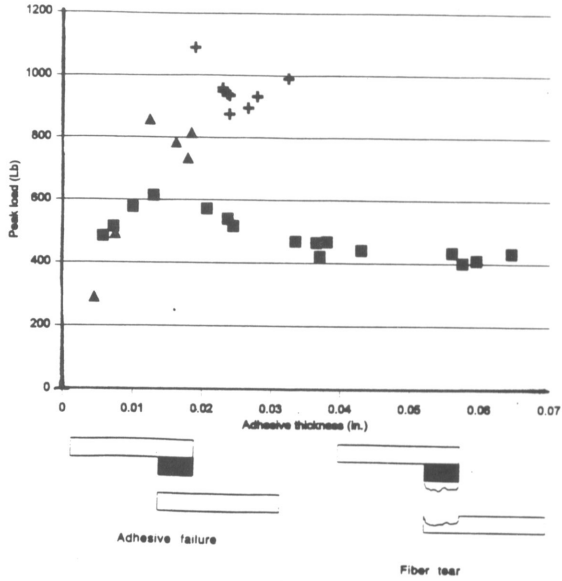

Fig.1 Effect of adhesive thickness on peak load. ■, ▲, and + represent 0.5", 1.0" and 1.5" overlap lengths.

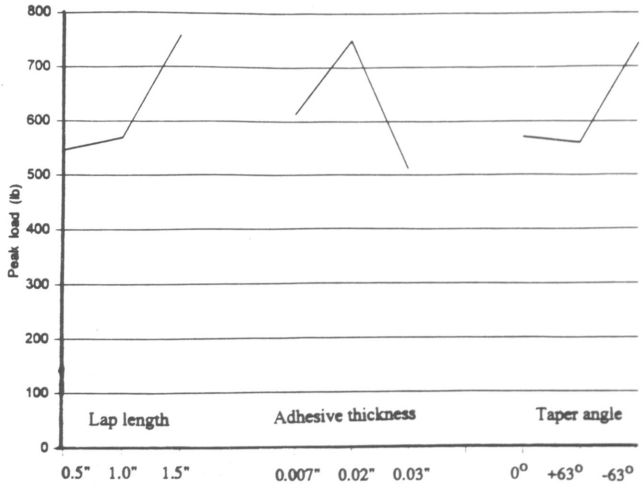

Fig. 2 Main effects of the lap length, adhesive thickness and taper angle on peak load.

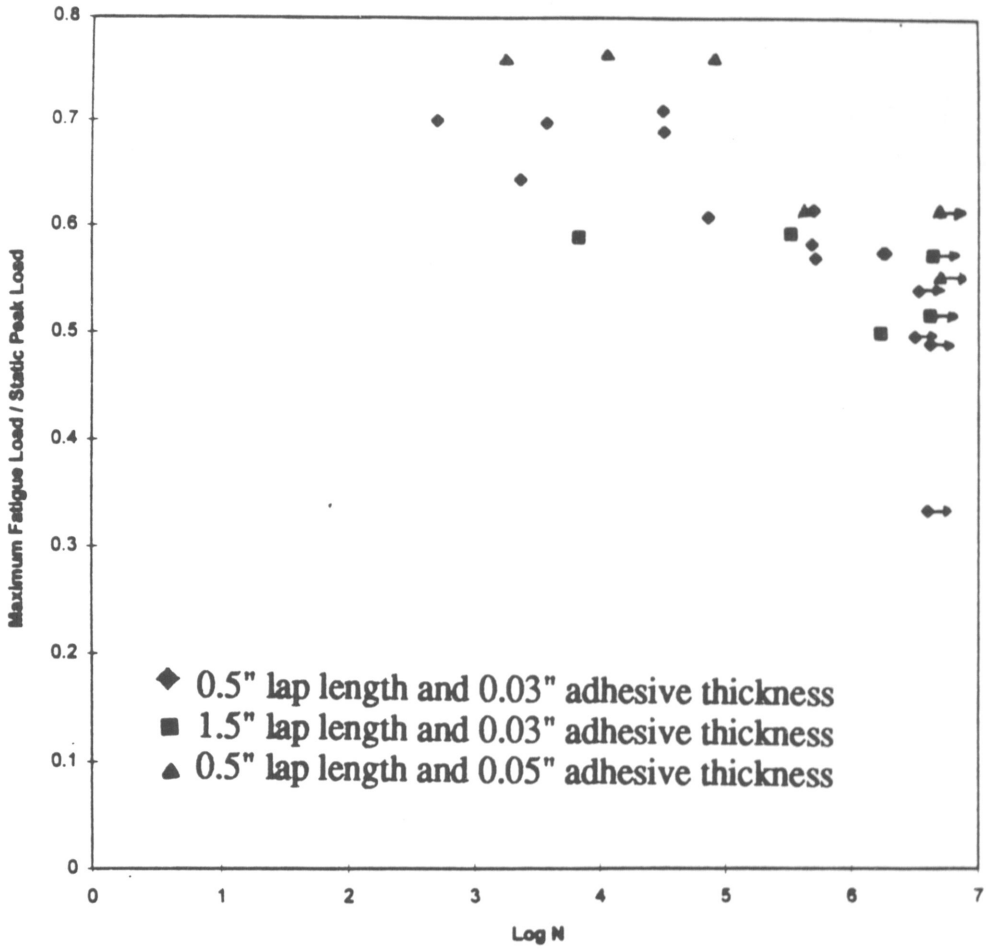

Fig. 3 Effects of lap length and adhesive thickness on fatigue tests of SMC-SMC single lap joints.

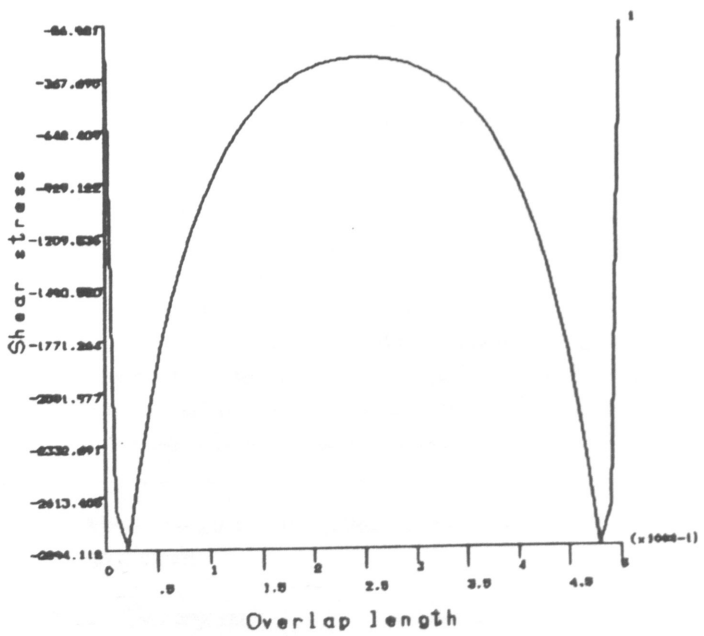

Fig. 4. Shear stress distribution at midthickness of the adhesive.

REPORT BRIEF

Modeling and Optimization of Curing in Thick Section Laminated Composites Using Neural Networks

June 19, 1996

RESEARCH EXCELLENCE AND ECONOMIC DEVELOPMENT FUND
PRODUCT QUALITY RESEARCH CENTER
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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ASSISTANT	Partha Roy Research Assistant	

BACKGROUND

Laminated composites used in aerospace and marine industries contain carbon- or glass-fiber reinforced epoxies which are processed at high temperature and pressure in an autoclave. The curing time, which determines the manufacturing cost and productivity of such composites, depends on many factors including the thickness. Thin section laminate curing has been studied both theoretically and experimentally by many investigators. Recently, more emphasis is being placed in thick section laminates for which very limited experimental data exist.

OBJECTIVE

The objective of this project is to develop an artificial neural network simulation model of curing thick section laminated composites and optimize various process parameters to obtain minimum cure time.

APPROACH

The curing of thick section laminated composites is characterized by complex relationships among the input variables such as temperature, viscosity, pressure, thickness and time and output variables such as cure rate and degree of cure. Analytical determination of these relationships requires simplifying assumptions. Neural networks provide an attractive alternative to modeling such a complex process. A trained network can perform highly complex mappings between the input and the output variables, thereby inferring subtle relationships between these variables which are otherwise elusive and intractable.

The training of neural networks for modeling thick section laminated composites requires experimental data which are not available in the literature. This has prompted us to conduct a set of curing experiments to generate such data. A heated hydraulic press is being used to cure glass-fiber reinforced composites. The prepegs are layered up to a certain thickness and cured under a set of heating schedules similar to those used in industry. From these experiments neural network training data are extracted and normalized to use with a commercial neural network training package, NeuralWare. Once a satisfactory model for this process is obtained, optimization to reduce total cure time will be carried out.

RESULTS

About 30 curing experiments with the following process input parameters have been conducted:

Heating rate: 2–8°C/min.

Dwell time:	1–2 hrs.
Dwell temperature:	100–130°C
Cure temperature:	160–180°C
Thickness:	200–400 plies

The output from the network is total cure time. From this data normalized neural network training vectors are extracted. The network architecture and the training algorithms are being currently investigated.

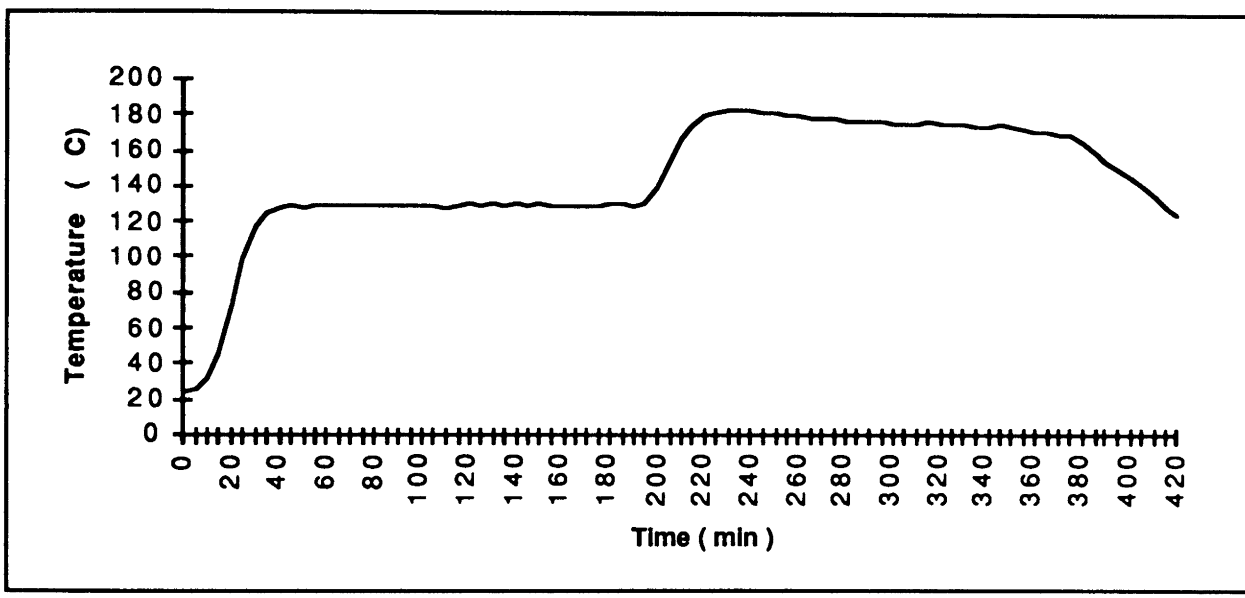

Fig 1. Temperature profile of a 200 plies thick composite curing

CONCLUSIONS

This is a project currently in progress. The experimental data collected corroborate theoretical expectations and are themselves a valuable outcome of this project.

IMPACT

1. The use of composites in general and thick section laminated structures in particular is on the rise. Even a small improvement in the manufacturing process resulting from the knowledge gained from this project will result in significant positive impact on the cost and quality of the products.
2. The work in this project will be reported in the literature and used as case study in ME589 (a graduate course on composite materials) and ECE 583 (a graduate course on neural networks).
3. This project has been the basis of a master's thesis for a graduate student in the electrical and computer engineering department.

REPORT BRIEF

Refrigerant Control of an Automobile Vapor-Compression Refrigeration System

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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PARTNER	Climate Control Division, Ford Motor Company	
ASSISTANTS	Paul D. Rogers Graduate Research Assistant	David Standaert Undergraduate Research Assistant

BACKGROUND

A current automobile refrigeration system control technique is to control the flow of refrigerant by cycling the compressor and metering the flow using a calibrated tube to satisfy evaporator demand, a technique referred to as the cycling clutch orifice tube (CCOT). The CCOT strives to achieve steady-state operation by controlling refrigerant mass flow to compensate for load variations caused by transient driving conditions (e.g., stop-and-go city driving, changing A/C operating mode from recirculation to fresh air). These load variations increase pressure drop and heat transfer losses within the refrigeration system. Preliminary investigation suggests that electronically controlling refrigerant flow in an automobile refrigeration system may offer some improvement over a current automobile refrigeration CCOT. This improvement is possible because the electronics permit the use of advanced control methods to minimize superheat conditions during high transient loads. The improved system uses an electronically controlled expansion valve to regulate the refrigerant flow necessary to maintain the desired superheat condition. This improved system is referred to as the intelligent cycling electronic expansion valve (ICEXV).

OBJECTIVE

The purpose of this research is to investigate an improved method of refrigerant control in an automobile refrigeration system and make a comparison to a current automobile refrigeration system based on thermodynamic principles.

APPROACH

The approach for this research project is divisible into two phases. Phase one is the instrumentation and calibration of the Lincoln Mark VIII automobile and data acquisition system. Temperature, pressure, and relative humidity sensors are mounted in the Mark VIII refrigeration system, engine compartment and passenger compartment as necessary. The data are automatically collected utilizing a laptop computer and Iotech Daqbook mounted in the vehicle. This instrumentation collects the necessary data to thermodynamically characterize the Mark VIII's environmental control system. Phase two of the project is to collect data for several operating conditions, such as initial pulldown of a heat-soaked passenger compartment, engine idling, 30 mph city driving, and 60 mph highway driving, and compare the performance of the CCOT and ICEXV systems.

RESULTS

Phase one, instrumentation of the MARK VIII and calibration of the data acquisition system, is complete. A total of thirty-five thermocouples, three relative humidity sensors,

and five pressure transducers characterize the vehicle environmental control system. Five thermocouples and the pressure transducers are placed in the refrigerant system to provide information about its thermodynamic state. The sensors are placed according to Figure 1.

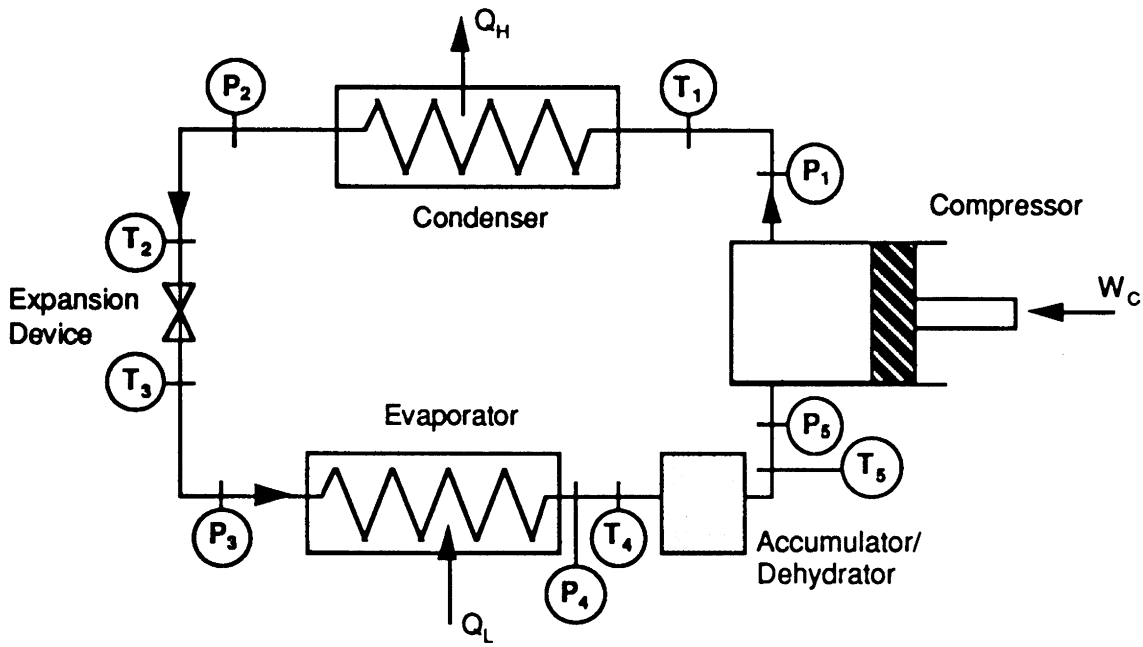

Figure 1: Flow Schematic of Automotive Refrigeration System

Preliminary results of the CCOT system operating under pulldown conditions are presented below. An example of a pulldown condition is an automobile sitting in a parking lot on a hot summer day. This condition requires the refrigeration system to cool a passenger compartment from a very high initial temperature. Figure 2 is the superheat, difference between the temperature measured by the thermocouple (T_4) and the saturation temperature corresponding to the pressure, at the exit of the evaporator (P_4). The variation of superheat has an exponential decay, from initial state to a final state, where it reaches a steady state after approximately ten minutes.

The system experiences a one-percent reduction in refrigerating capacity for every four degrees of superheat. Thus, the goal of the control system is to reduce the absolute superheat and improve the response time of the refrigeration system. Data for the ICEXV controller under similar conditions will be collected and a comparison will be presented based on absolute superheat and the refrigeration system response time.

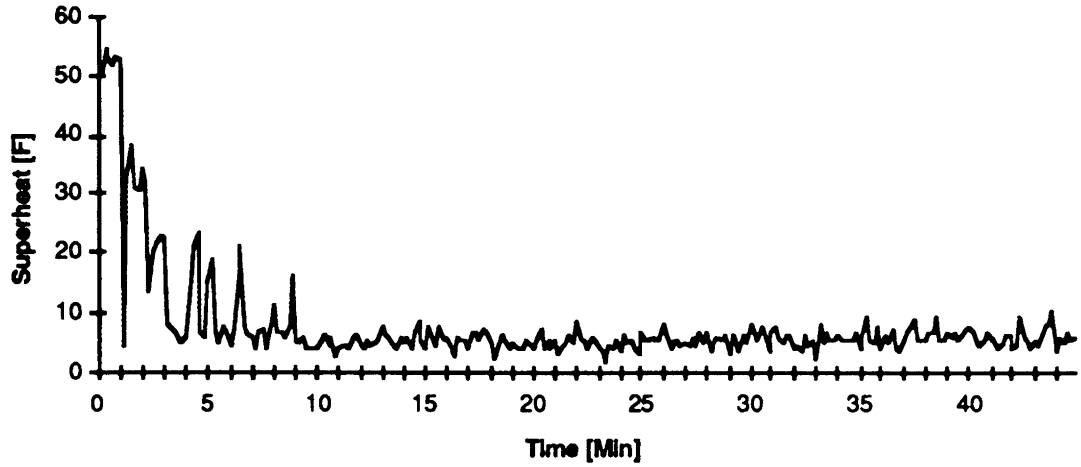

Figure 2: Superheat at Evaporator Exit

IMPACT

The results of this study will provide a preliminary comparison of system performance with a CCOT vs. an ICEXV. The results will provide an indication of advantages and disadvantages associated with electronic expansion valves for refrigerant metering during various operating conditions.

REPORT BRIEF
Simulation of In-Cylinder Flows

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

AUTHORS Subrata Sengupta, Mechanical Engineering; Vladimir Griaznov, Ford Motor Company

PARTNERS Gary Strumolo, Derlon Chu, Habib Affes, Laurine Leep, and Nizar Trigui, Ford Motor Company

BACKGROUND

Understanding of in-cylinder flows is crucial in predicting combustion behavior, emissions and efficiency. Of particular interest are the scavenging phenomena in two-stroke engines and flow past valves in four-stroke engines.

Two-stroke engines have both advantages and disadvantages over their four-stroke counterparts. Simple engine design, low weight, low manufacturing costs, and a more favorable torsional force diagram are all attractive features. Disadvantages involve higher HC emissions, poorer volumetric efficiency, higher thermal load, and a higher percentage of residual gas.

OBJECTIVE

The objectives are to analyze a two-stroke engine's sensitivity to port geometry, especially the influence on scavenging parameters, and to develop reliable computational models for flow past valves in four-stroke engines.

APPROACH

FIRE, a finite volume, body-fitted coordinate numerical code, was selected for simulating the non-reacting flow. Implementation on an HP-735 was chosen for cost and ease of use considerations. The code is now executed on the workstation at the University of Michigan-Dearborn (UM-D) by users in Ford Scientific Labs and Ford Germany and UM-D investigators. The technical approach consists of developing robust grids that produce convergent solutions. Comparison of computational results with other models and experiments is used to evaluate the reliability of the models.

RESULTS

Simulations for two-stroke and four-stroke engines were conducted. For the two-stroke engine, calculations for 3000 and 5500 rpm were done.

The project has accomplished the following: (1) reliable grids have been generated; (2) grid compression and rezoning algorithms have been tested with moving piston; (3) fluid physics parameters have been qualitatively analyzed and have been found to be realistic; and (4) comparison with results from 1-D lumped parameter model, PROMO, and STAR-CD is satisfactory.

Numerical simulation of the scavenging processes in a two-stroke engine using the FIRE code gives new information about the 3-D structure of the gas flow in the cylinder and distribution of fresh charge during scavenging. Modeling the engine using the cylinder, combustion chamber, piston surface (with lip and bowl), and exhaust port geometries, as well as taking advantage of the symmetry of the geometry, is a reasonable approximation to

the complete geometry (including three cylinders and crankcase). However, such an approach requires additional experimental data or theoretical results about conditions in inlet and exhaust manifolds to complete the model.

Calculations show that exhaust manifold geometry is an important element in controlling scavenging. The position of the exhaust valve drastically changes the pressure difference between cylinder and exhaust manifold and as a result strongly influences scavenging.

It was found that mutual influence of the cylinders in a fired engine on the scavenging process is not negligible. For a three-cylinder engine, increasing pressure in the exhaust manifold at a crank angle of 210 degrees decreases fuel loss and improves scavenging parameters for 5500 rpm. Detailed calculations are necessary to study this influence for different rpm and to use if for scavenging control.

It is possible to use PROMO results for closing the 3-D FIRE model. The PROMO results reflect such elements as increasing pressure in the exhaust manifold due to blowdown from another cylinder and also the unsteady velocity in inlet ports due to the time-dependent pressure in the crankcase. It was found that when PROMO results are used as boundary conditions, the calculated results for average cylinder pressure agree well with the PROMO results (within 5–10%) as a diagnostic check. With fixed boundary conditions for pressure in the exhaust manifold (on the order of 100 KPa) for crank angles of 214 to 270 degrees the difference was significant (more than 100% difference).

Investigations of the influence of inlet flow direction on scavenging efficiency for the high-load and high-speed case (5500 rpm, WOT) using PROMO results for boundary conditions at the inlet ports and exhaust manifold show only a weak dependence of the scavenging efficiency on flow direction. The calculations do not give conclusive evidence to suggest design changes for the transfer ports.

CONCLUSIONS

Results indicate that workstation implementation of FIRE is practical for use as a design tool. A complete cycle (i.e., .02 sec) of real time takes about 40 hours of CPU time. The costs are significantly less than supercomputer usage; especially considering the delays of scheduling. Detailed 3-D time-dependent results can be obtained by FIRE with satisfactory comparisons with other simulations.

IMPACT

A new continuing education course in engine heat transfer was developed and delivered to Ford.

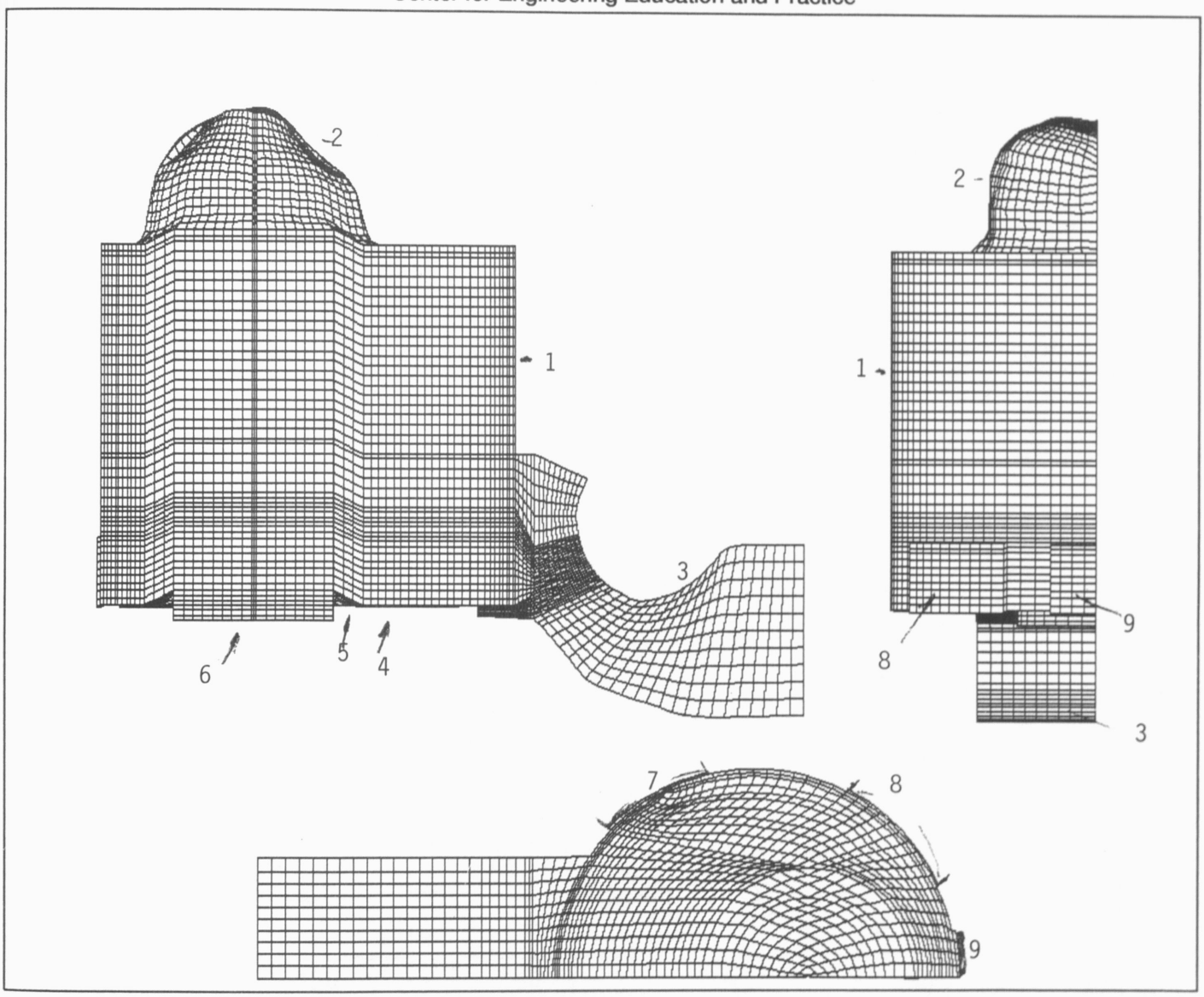

Fig. 1 Basic geometry. (1-cylinder, 2-combustion chamber, 3-exhaust manifold, 4-piston surface, 5-piston lip, 6-piston bowl, 7-main port, 8-auxiliary port, 9-rear port)

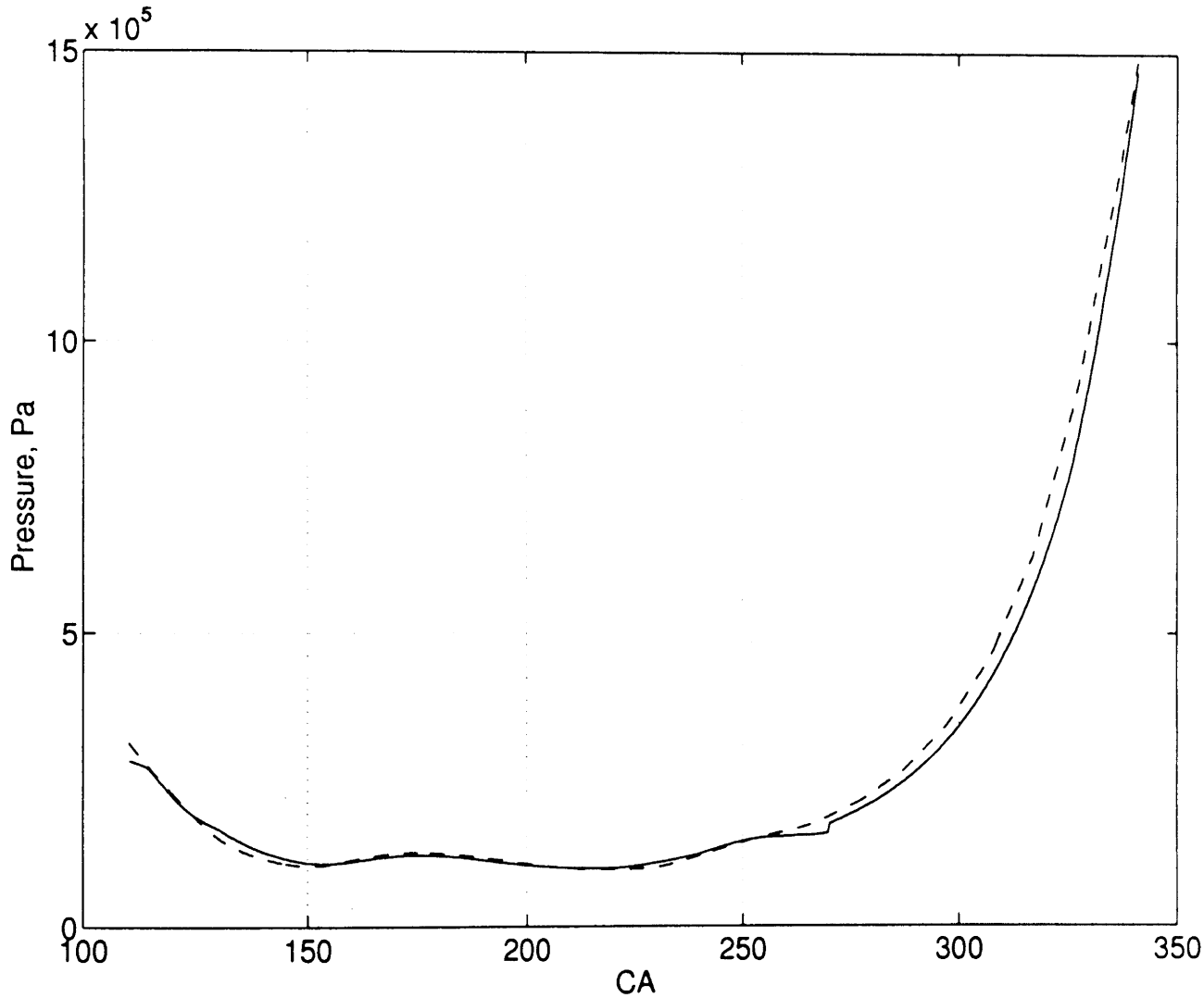

Fig. 2 Average pressure in the cylinder, obtained as a result of calculations (solid line) and PROMO data (dashed line).

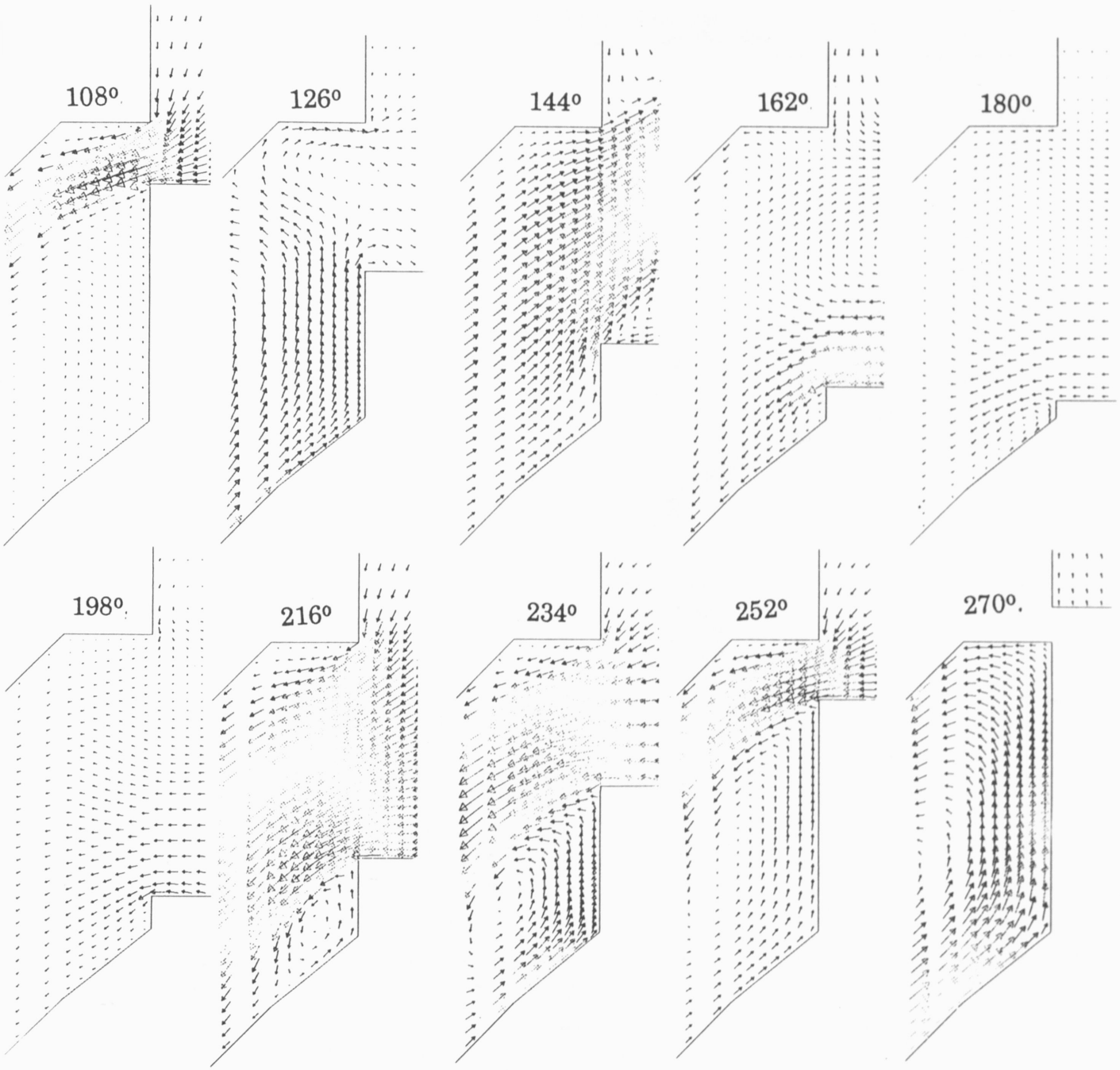

Fig. 3 Velocity vectors near exhaust port for RPM=3000. Figures show CA value.

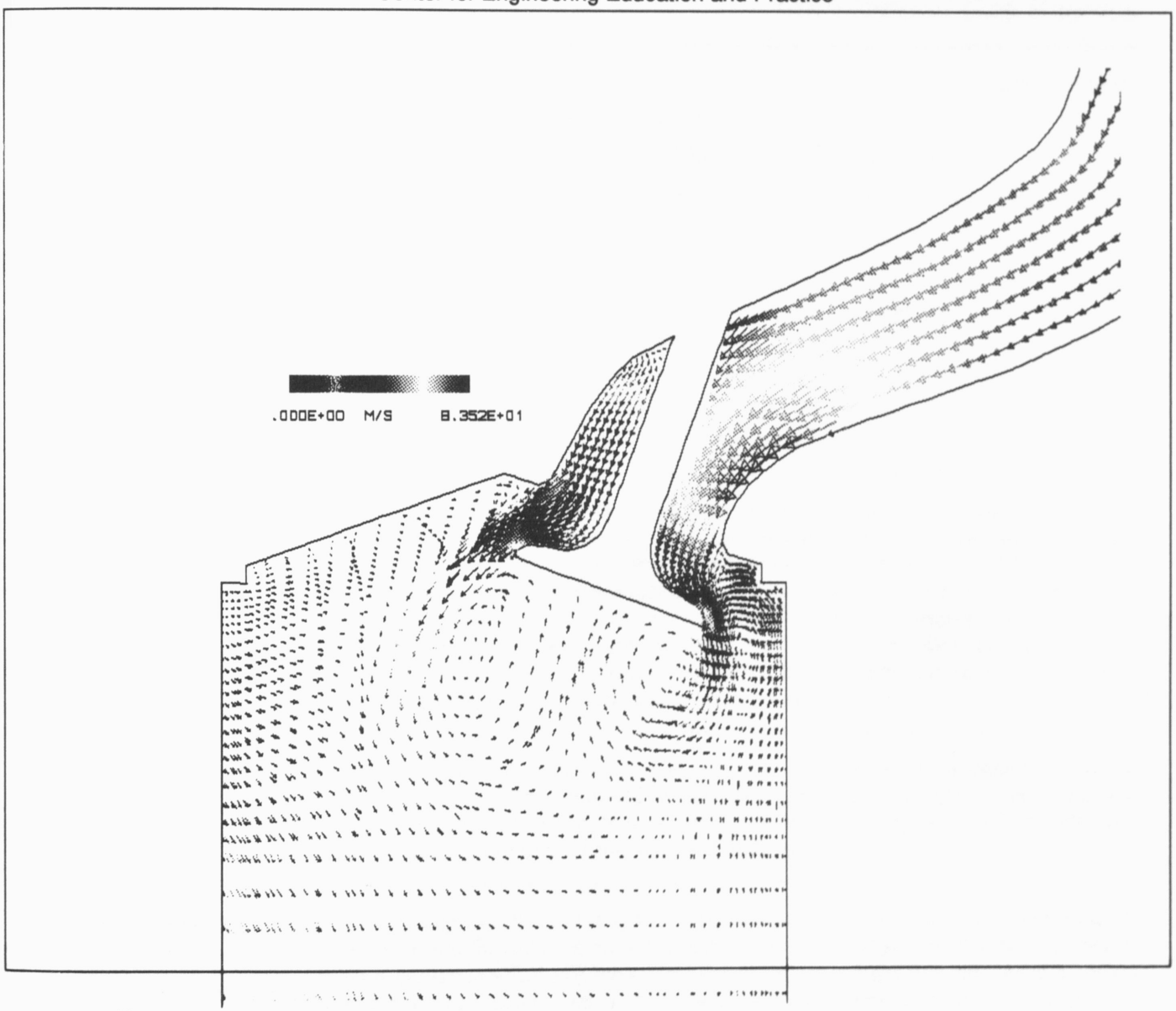

Fig. 4 Flow around intake valve.

REPORT BRIEF

Hydrocarbon and Oxides of Nitrogen in Lean Burn Natural Gas Engines

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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PARTNER	Addy Majewski Diesel Controls Ltd.	George Frame and Jeff Lyjak Ford Motor Company
ASSISTANTS	N. Patro, Research Associate A. Hassaneen, Visiting Scholar K. Drouillard, Research Assistant	

BACKGROUND

In the last few years, there has been a surge of interest in natural gas as a fuel for light- and medium-duty vehicles. This interest stems from already enacted exhaust emission regulations requiring considerable reduction in hydrocarbons (HC), oxides of nitrogen (NO_X), and carbon monoxide (CO). The magnitude and character of exhaust emissions from natural gas fueled engines vary depending on trade-offs made between performance, emissions, and efficiency. By utilizing natural gas properties such as its flammability and higher octane number, it may be possible to design a lean-burn, high compression ratio engine to meet emission requirements without sacrificing performance.

OBJECTIVE

The objective of the investigation was to assess (1) the extent to which variations in air-to-fuel ratio (A/F) could be controlled in lean-burn, natural gas fuel injected vs. carbureted engine (2) the extent to which NO_X could be reduced and its impact on HC emission, and (3) trade-offs between exhaust emissions and fuel economy.

APPROACH

A 4.6 liter, high compression ratio spark ignition (SI) engine was used in the experiments. The engine was fueled by natural gas using a sequential injection system. A universal exhaust gas oxygen (UEGO) sensor, calibrated for natural gas fuel containing a known concentration of methane, was used to monitor A/F ratio and its variations. Exhaust gases were continously sampled for HC, NO_X, and CO. In addition, oxygen concentration in the engine exhaust was measured by a Horiba analyzer. Tests were conducted at steady state at various engine speeds, loads, and equivalence ratios (ER) ranging from stoichiometric to 0.6.

RESULTS

The sensor output was processed and correlated with its calibration to arrive at variations in A/F ratio. At stoichiometric condition the variation in A/F ratio was found to be +/- 0.08 while at ER=0.6 it was within +/- 0.4, as shown in Figure 1. These variations were significantly lower than those reported earlier in an engine using a mixer type of fuel system. Even at the very lean A/F ratio the COV in A/F ratio was about 1%, as shown in Figure 2.

The increase in COV in A/F ratio with decreasing ER may be attributed to injector characteristics at very small pulse widths and partial burning of mixture due to flame quenching at relatively low gas temperatures.

Figures 3 and 4 show the effects of ER and bmep on engine thermal efficiency at MBT timing. The dependence of thermal efficiency on ER is not significant at light loads but at higher loads thermal efficiency was influenced by ER. The best efficiency was realized at ER of about 0.7 where the burning process is quite reliable and the pumping losses are low due to relatively high manifold pressure.

Contours of constant NO_x and HC levels in engine exhaust are shown in Figures 5 and 6, respectively. Reducing ER from stoichiometric to about 0.6 reduced NO_x levels significantly at all engine loads. In fact, NOx levels at this ER were much lower than those realized in an engine operated at stoichiometric condition with feedback control and a 3-way catalyst. Reducing ER from 1.0 increased HC levels but the major increase was between 0.65 and 0.6. Furthermore, most the HC were in the form of methane which has relatively low reactivity. The concentration of non-methane HC was between 5% to 18%.

The trade-offs between ignition timing and exhaust emission are shown in Figs. 7 and 8. Off-optimum ignition timing did not affect HC emissions much but had strong influence on NO_x, particularly for ER>0.7. Retarding ignition by 6 degrees from MBT reduced NO_x by about 35% at ER=0.7 and 350 kPa bmep while the HC emissions were hardly affected. Of course, thermal efficiency drops slightly with retarded timing but the reduction in NO_x compensates for the loss.

CONCLUSIONS

The fluctuations in A/F ratios were less sensitive to engine load and speed but were found to depend on nominal A/F ratio. But the variations in A/F ratio even at 0.6 equivalence ratio were low, within +/- 0.4 A/F ratio. Lean-burn operation resulted in significant reduction in NO_x but HC emissions increased with decreasing equivalence ratio, particularly when it was reduced from 0.7 to 0.6. Improvement in engine thermal efficiency was realized with lean-burn operation, the best efficiency was around 0.7 equivalence ratio. Over the entire range of A/F ratios the COV in A/F ratio, NO_x, and HC were significantly lower than those realized in an engine using mixer or carburetion-type fuel systems. A well controlled fuel injection system should be able to improve operation and performance of a lean-burn natural gas engine.

IMPACT

This project helped train several undergraduate and graduate students in combustion engines and alternate fuels area. The results of the investigation are currently included in combustion engines course offered to undergraduate and graduate students. A course on "Fuel Systems", developed for Ford Motor Co., includes a module on alternate fuels including natural gas fuel.

ACKNOWLEDGED

This work was partly supported by a grant from the Center for Engineering Education and Practice, the Government of Egypt through student support, the Ford Motor Company and Diesel Engine Controls(Canada) through in-kind support.

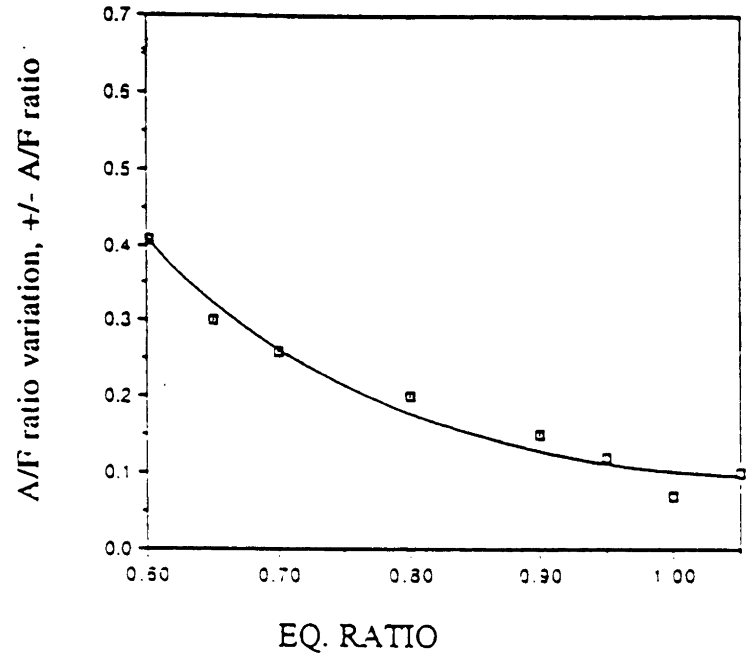

Fig. 1. Air-to-Fuel Ratio Variation with Equivalence Ratio (2100 rpm, 150 kPa bmep, MBT spark)

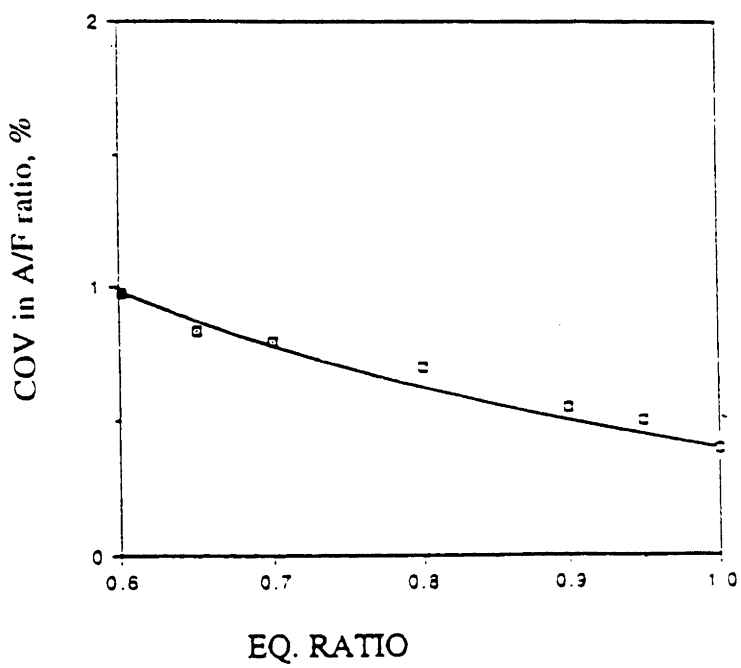

Fig. 2. COV in A/F Ratio with Equivalence Ratio (2100 rpm, 150 kPa bmep, MBT spark)

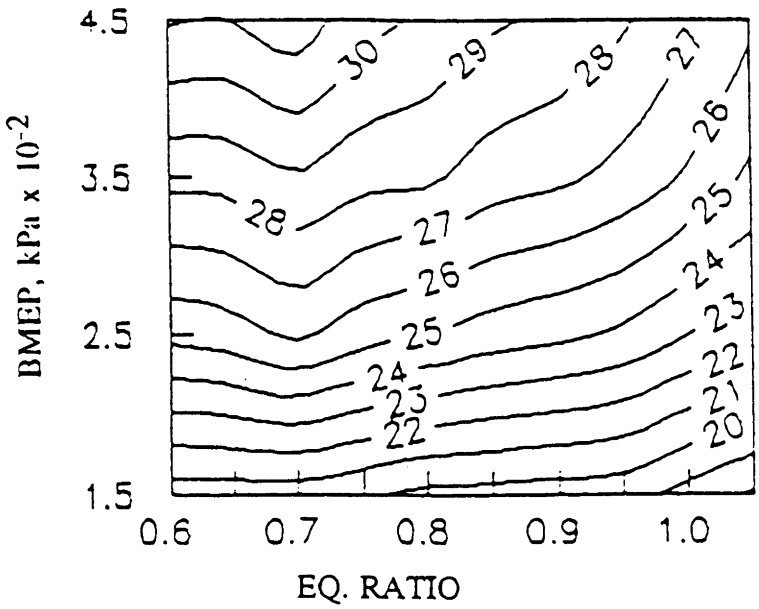

Fig. 3. Thermal Efficiency at 1500 rpm
(MBT spark timing)

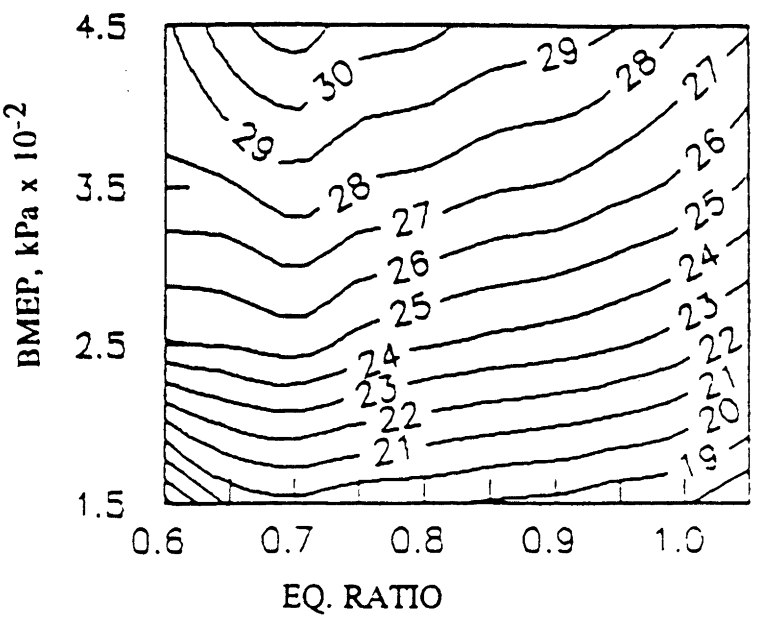

Fig. 4. Thermal Efficiency at 2100 rpm
(MBT spark timing)

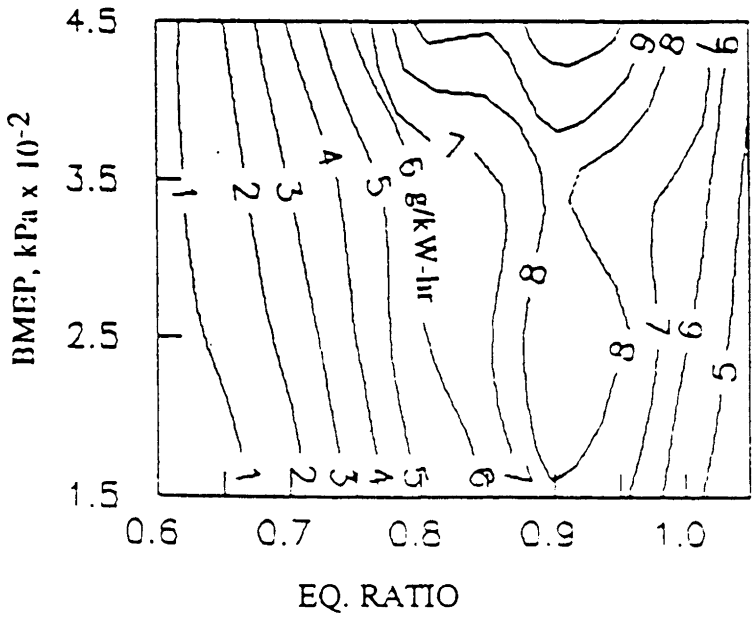

Fig. 5. NOx Variations With Equivalence Ratio (2100 rpm)

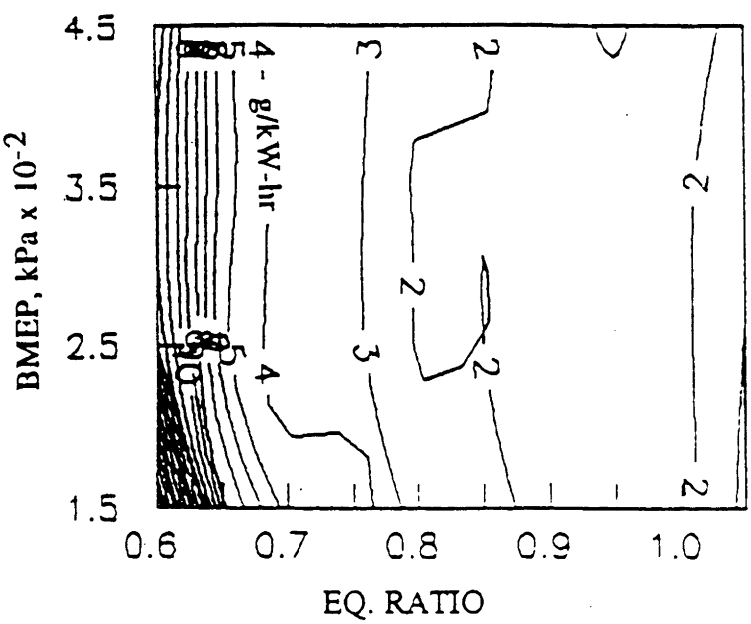

Fig. 6. HC Variations With Equivalence Ratio (2100 rpm)

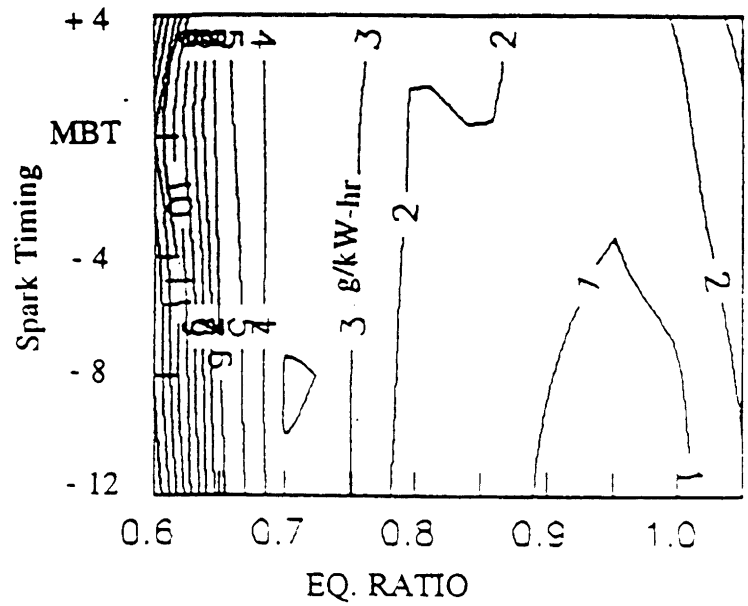

Fig. 7. HC Emissions Trade-Offs at 2100 RPM, 350 kPa bmep

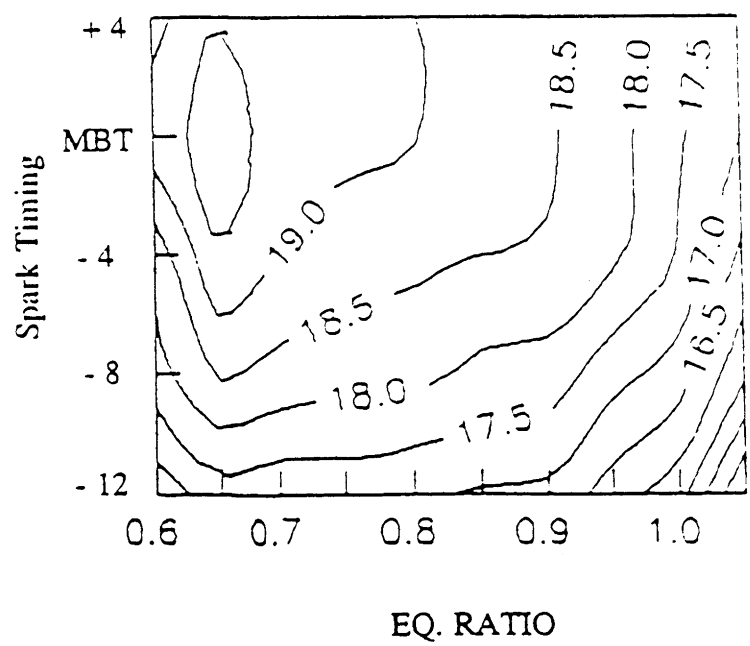

Fig. 8. NOx Emissions Trade-Offs at 2100 RPM, 350 kPa bmep

REPORT BRIEF

An Integrated System for the Design, Analysis and Manufacturing of Face-Hobbed Hypoid and Spiral Bevel Gears

June 19, 1996

CENTER FOR ENGINEERING EDUCATION AND PRACTICE
SCHOOL OF ENGINEERING, UNIVERSITY OF MICHIGAN-DEARBORN

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PARTNER	Wei-Jung Tsung Spicer Axle Division, DANA Corporation
ASSISTANT	Zhi Wu Research Associate

BACKGROUND

Hypoid and spiral bevel gears can be manufactured by either face milling or face hobbing. Due to the maturity of face milling technology, it is more widely used in the gear industry even though the face hobbing method is more productive and produces gears with lower operation noise. Existing multi-axis CNC gear generators are capable of both face milling and face hobbing, but the software technology, similar to that for face milling, must be enhanced in order to popularize face hobbing.

OBJECTIVE

The primary objective of the research is to develop a computer integrated software system for the design and analysis of face hobbed gears. The system is applied to quantitatively analyze the quality of gears by simulating the meshing between gears with face hobbed tooth geometry and calculate the precise gear tooth geometry for CMM measurement.

APPROACH

The research work is based on the theory of gearing and conjugate surfaces and on the simulation of gear generation and meshing. The simulation of gear generation determines the gear tooth surface geometry up to the curvature level. The meshing between gears generated with a given machine tool set-up is simulated by tooth contact analysis (TCA). The output of TCA provides the information on gear transmission errors and contact patterns.

RESULTS

The integrated computer software for the calculation of tooth geometry and tooth contact analysis has been developed. The software has been applied for a prototype face hobbed hypoid gear drive. Reasonable agreement between the geometry calculated by simulation (Fig. 1) and the geometry measured on manufactured gear prototypes has been achieved. The TCA results on transmission errors and contact patterns are agreeable to those measured by single flank tests (Fig. 2).

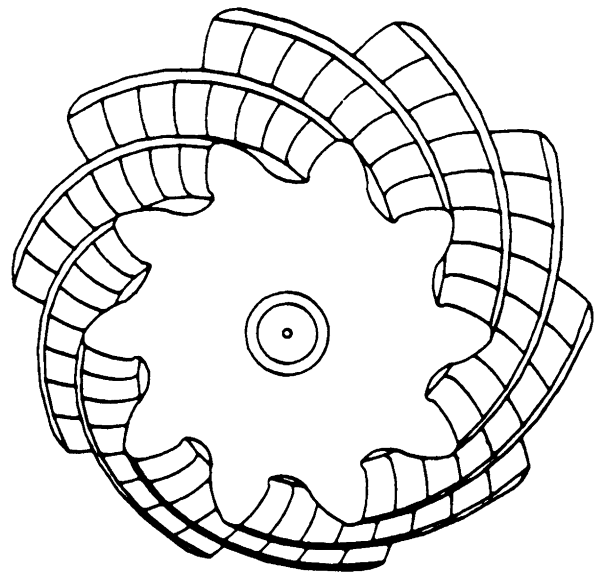
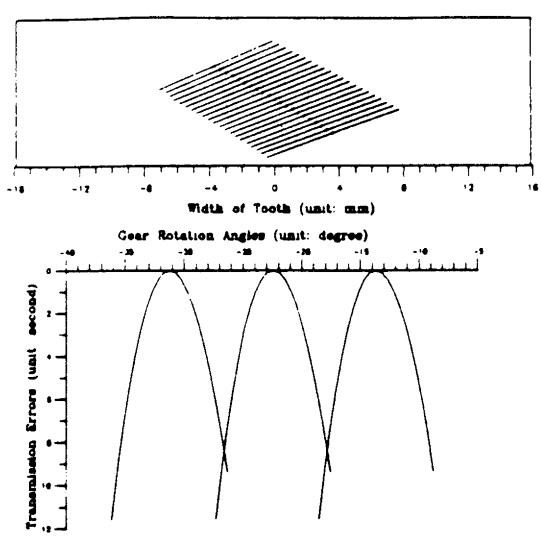
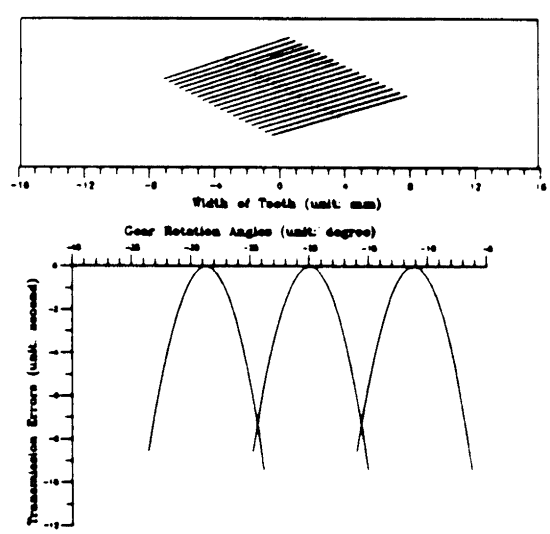


Fig. 1



a) Gear: Convex, Pinion: Concave, V/H: -4/23



b) Gear: Concave, Pinion: Convex, V/H: -2/6

Fig. 2

IMPACT

The research results provide an analytical tool for the determination of face hobbed gear geometry and the analysis of tooth contact without cutting the gears. This is helpful in speeding up gear product development and reducing the cost of gear prototyping.

The results of the research is partially integrated in the newly created graduate course "Theory of Gearing and Applications." In the course, students work on projects involving the simulation of gear generation process and develop related computer codes. In the projects, students apply the theory of gearing for certain types of gears and gain hands-on experience in gear design and manufacturing.

PUBLICATIONS

Two papers based on the research have been accepted for international technical conferences sponsored by ASME as listed below:

Y. Zhang and Z. Fang, "A Tooth Contact Analysis Model for Crossed Axis Helical Gears Under Load," *Proceedings of the 1996 ASME Design Engineering Technical Conference and Computers in Engineering Conference*, August 18–22, 1996, Irvine, California, Paper No. 96-DETC/MECH-1201.

Y. Zhang and Z. Wu, "Offset Face Gear Drives: Tooth Geometry and Contact Analysis," *Proceedings of the 7th International Power Transmission and Gearing Conference*, October 6–9, 1996, San Diego, California, Paper No. 031PTG96.

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